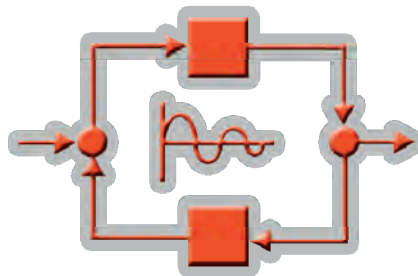




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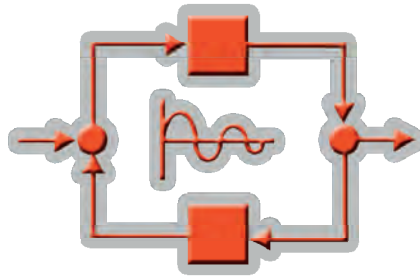
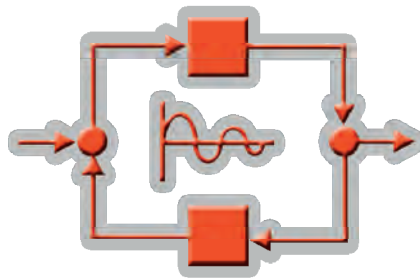


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ABSTRACT= {The electric power industry is in transition to a deregulated
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@ARTICLE {
P1111130671,
AUTHOR = {V. Anantha Lakshmi and T. Brahmananda Reddy and V. C. Veera
Reddy and M. Surya Kalavathi},
TITLE = {Reduction of Common Mode Voltage using Space Vector Based
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JOURNAL = {ICGST International Journal on Automatic Control and Systems
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ABSTRACT= {In conventional space vector pulse width modulation (CSVPWM),
the complexity involved in calculation of sector and angle information is more.
Moreover common mode voltage (CMV) is more due to usage of zero voltage
vectors  $V_0$  and  $V_7$ . To reduce CMV and complexity involved in CSVPWM
algorithm, this paper presents a simplified active zero state PWM algorithms
(AZPWM) using the concept of imaginary switching times in which actual
switching times are calculated from the sampled phase voltages. In the proposed
approach, for the reduction of CMV instead of using zero voltage vectors two
active opposite voltage vectors with equal time duration are utilized with two
adjacent active voltage vectors to compose required reference voltage vector.
Though these AZPWM methods reduce the computational burden involved in
calculation, they still suffer from steady state ripples in torque, flux and current.
To reduce the ripples in steady state, a hybrid PWM (HPWM) technique is
developed in which stator flux ripple analysis is done for all the AZPWM
sequences. To validate the proposed PWM algorithms, numerical simulation
studies have been carried out v/f controlled induction motor drive using MATLAB-
Simulink and results are presented and compared},
NOTE={imaginary switching times, induction motor drives, PWM inverter,
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AUTHOR = {J. Sridevi and J. Amarnath and G. Govinda Rao},
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ABSTRACT= {Deregulation of electric industry has a direct impact on the
increasing number of transactions. This lowers the available margin and leads to
the increased congestion of transmission lines. Thus the system becomes more
vulnerable to collapse. Analyzing the system security and congestion, and
determining their effects on pricing becomes more important than ever in the
deregulated environment. This paper proposes a method for the placement of
Flexible AC Transmission System devices in deregulated power system to reduce
congestion. Locational marginal price is used to study the effect of congestion in
the pricing model. The proposed method is based on Locational Marginal Price
differences of Optimal Power Flow to find the optimal location of Thyristor
Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Angle
Regulator (TCPAR) devices. The overall objective function can be either to
minimize the congestion rent or to maximize the social welfare. The proposed
method is tested on an IEEE 24rts system, an IEEE 57 bus system and an IEEE
118 bus system. Results shows that the proposed method for TCSC is capable for
reducing the congestion rent and for TCPAR is capable for maximizing the social
welfare},
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abstract={Variable sampling is important issue for the motor drives
with low resolution position sensors. This paper proposes a variable
sampling effect for Brushless DC motor (BLDC) drives using fuzzy PI
(proportional and integral) controller using SIMULINK. The
controller uses three fuzzy logics and three PI controllers to achieve
variable sampling control. The simple structure of the fuzzy PI
controller for BLDC motor considering variable sampling effect is not
only implemented easily, but also robust in variable speed control
system. The Simulink software was used to simulate the proposed
scheme. The results are obtained for variable speed.},
note={variable sampling, discrete-time, SIMULINK, Fuzzy, PI
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title={Use of Gain Scheduling Fuzzy Controller and Fuzzy Observer
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abstract={In this paper, an Adaptive Neuro Fuzzy Inference System
(ANFIS) used to design a gain scheduling fuzzy controller, and fuzzy
reduced order observer based on gain scheduling method. The
nonlinear model of a magnetic bearing system with imbalance
complicated, and the coupling between various states cannot
neglect. First, the proposed fuzzy control system constructed for
decentralized linear systems at a wide range of operating points of
air gap and current for different values of rotational speed. Second,
the data collected used as training data for ANFIS to construct if-
then rules and membership function. Results show that the
proposed fuzzy control system achieved stability and can eliminate
disturbances at any rotational speed},
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volume={11},
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pages={41--48},
abstract={In recent years, the research has been focused to find
out different solutions for the induction motor control having the
features of precise and quick torque response and reduction of the
complexity of field oriented algorithms. The direct torque control
(DTC) technique has been recognized as the viable solution to
achieve these requirements. The direct torque control of induction
motors fed by two level inverter has certain drawbacks like more
torque, flux and current ripples in steady state, which results in
incorrect speed estimations. This paper presented the direct torque
control of induction motor fed by a three level neutral point clamped
inverter used in high power applications. To improve the speed
performance of the drive against uncertainties caused by load
disturbances, an integral switching surface sliding mode speed
controller (SMC) is proposed. To validate the proposed method,
simulation results are presented.},
notes={Direct torque control, Sliding mode control, Neutral point
clamped inverter.}
}
```



Contingency Analysis under Deregulated Power Systems

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Abstract

The electric power industry is in transition to a deregulated market place for power transactions. In deregulated environment, participants are interested in maximizing their own profits, regardless of the system-wide profits. It is perceived that the competition will reduce the price of electricity for retail customers; however, the key issue for participants is related with the price definition to remain competitive. Contingency Analysis of a power system is a major activity in power system planning and operation under deregulated environment. In general an outage of one transmission line or transformer may lead to over loads in other branches and/or sudden system voltage rise or drop. This paper focuses on developing an algorithm for Multiple Line Outage Distribution Factor (MLODF) and to take corrective actions based on sensitivity for multiple outages. The developed algorithm was tested on three test systems; six bus, thirty bus and thirty seven bus test cases. The test results demonstrate that given situational awareness the algorithm provide additional decision support that can be used for remedial actions and/or for recovery after multiple outages. Integrating these into a power system energy management system (EMS) will provide a tool for operators to have a better understanding of the system before and during an extreme condition.

Keywords: Deregulation, Contingency Analysis, Multiple-line outages, power system control.

1. Introduction

The electric power industry has been dominated by large utilities that had an overall authority over all activities in generation, transmission and distribution of power within its domain of operation. Such utilities have often been referred to as vertically integrated utilities. The basic objective of the operator in such vertically integrated utilities would be to maintain reliable and uninterrupted services to the load. The

introduction of deregulation has brought several new entities in the electricity market place, while on the other hand redefining the scope of activities of many of the existing players. Variations exist across market structures over how each entity is particularly defined and over what role it plays in the system [1-2]. Contingency analysis is a software application run in an energy management system to give the operators an indication of what might happen to the power system in the event of an unscheduled equipment outage. A direct approach to identify contingencies that cause component limit violations would involve performing a full AC load flow for all conceivable outages. Contingency Analysis (CA) is one of the "security analysis" applications in a power utility control center that differentiates an Energy Management System (EMS) from a less complex SCADA system. Its purpose is to analyze the power system in order to identify the overloads and problems that can occur due to a "contingency". A contingency is the failure or loss of an element (e.g. generator, transformer, transmission line, etc.), or a change of state of a device (e.g. the unplanned opening of a circuit breaker in a transformer substation) in the power system. Therefore contingency analysis is an application that uses a computer simulation to evaluate the effects of removing individual elements from a power system[3-4].

The paper is organized as follows: Section (2) focuses on Contingency Analysis. Section (3) elaborates remedial action schemes for contingencies while Section (4) presents the algorithm for Line Outage Distribution Factor (LODF). The simulation results are presented and discussed briefly in Section (5). Section (6) concludes the work.

2. Contingency Analysis

Contingency analysis [5-6] gives the security status of the power system network and list of critical contingencies. Contingency analysis is achieved by running power flow cases after removing different elements of the power system network such as a transmission line, transformer, bus or generator. Contingency analysis helps us to look at the system's vulnerable points and allows possibly determining a solution offline ahead of time, because the



time available for the operator to react in real time situation is minimal.

As mentioned above contingency analysis is achieved by removing different types of elements. Outage types and their importance are explained below.

2.1. Types of contingencies

Transmission lines, transformers, generators and buses are the key components of power system network. Different kind of contingencies that can happen based on these important components are discussed in this section. Due to physical vulnerability of a transmission line, it is most prone to the outages due to various reasons starting from sagging on to a tree to higher current flowing through it. The desired voltage level is maintained using the transformers which step up/down the voltage according to the requirements. A transformer outage is also one of the important outages in the system.

Generators are the source of power for the system. Loss of generation causes many problems in the system and may lead to a blackout.

Buses are the main components of the power system network, particularly because of their connections in the system. All the transmission lines, transformers and generators are connected to the rest of the system through the buses. An outage of the bus is typically an outage of all the elements connected to that bus, which becomes very huge loss if the number of elements connected to that bus is higher. A bus outage is thus considered to be critical.

Thus different types of contingencies and their study will help in better planning of the system and helps the operator in preparing for them. Some events can cause outage of multiple components in the system causing more loss compared to single contingencies[7].

2.2. Types of violations

Line contingency and generator contingency are generally most common type of contingencies. These contingencies mainly cause two types of violations[8].

i. Low voltage Violations:

This type of violation occurs at the buses. This suggests that the voltage at the bus is less than the specified value. The operating range of voltage at any bus is generally 0.95-1.05 p.u. Thus if the voltage falls below 0.95 p.u then the bus is said to have low voltage. And if the voltage rises above the 1.05 p.u then the bus is said to have a high voltage problem. It is known that in the power system network generally reactive power is the reason for the voltage problems. Hence in the case of low voltage problems reactive power is supplied to the bus to increase the voltage profile at the bus and in the case of the high voltage reactive power is absorbed at the buses to maintain the system normal voltage.

ii. Line MVA limits violations:

This type of contingency occurs in the system when the MVA rating of the line exceeds given rating. This is mainly due to the increase in the amplitude of the current flowing in that line. The lines are designed in such a way that they should be able to withstand 125%

of their MVA limit. Based on utility practices, if the current crosses the 80-90 % of the limit, it is declared as an alarm situation. Different types of remedial actions to solve this problem are explained later in this paper.

2.3. Higher order contingencies

The outages or contingencies are generally denoted in terms of numbers such as “N-n”, where ‘N’ refers to the total number of elements of specific type in the system and ‘n’ refers to the number of those elements which are outaged. For example if one transmission line is outaged in the system then it is called an ‘N-1’ transmission line outage and if 3 elements are outaged in the system then it is called ‘N-3’ transmission line outage. Thus the outages with more than a single line outage are generally called higher order contingencies.. This paper focuses on developing corrective actions for higher order contingencies.

3. Remedial Actions Schemes

Remedial Action Schemes (RAS) are the key components for any power system utility planning. These are the steps which the utilities need to take in order to get the system back to its normal operation. Remedial Action Scheme (RAS) as the name suggests are the necessary actions which need to be taken to solve the violations caused by a contingency. Remedial Action Schemes are also defined as Special Protection Schemes (SPS) or System Integration Schemes (SIS)[8].

3.1. Types of remedial actions

- i. Shunt capacitor switching:
- ii. Generation Re-dispatch:
- iii. Load shedding:
- iv. Under load tap changing (ULTC)Transformer:
- v. Distributed Generation:
- vi. Islanding:

4. Line Outage Distribution Factor

The Line Outage Distribution Factor (LODF) is one of the important linear sensitivity factors which plays a key role in finding the effect of the critical contingencies and hence suggesting possible preventive and corrective actions to solve the violations in the system. LODF [9] calculates the impact on all other transmission lines in a network when a single transmission line goes out in a system. LODF is being used as an important tool for calculating the outage impact i.e. how severe is the outage and how it impacts the system. LODF is based on the DC power flow and is less accurate compared to the full AC power flow. It only calculates the MW flow and doesn't give any information about MVAR of the line or the bus voltages. Also DC power flow is a one way to gain speed of solution in a contingency analysis procedure by creating an approximated model of the power systems.

The Multiple Line Outage Distribution Factor (MLODF) calculates the impact on the transmission lines of the system when multiple lines are outaged in the system. LODF is widely used by industry, where not much as attention has been paid to the MLODF. The MLODF is very useful in calculating the impact on the system when higher order contingencies happen in the system.



Depending on the type of contingency MLODF can be used for MVA limitations of line during the multiple outages.

4.1. Algorithm for LODF

1. Input the branch data and bus data for the test case.
2. Calculate the number of buses and number of branches from the data.
3. Define the slack bus and its corresponding number.
4. Calculate the susceptance matrix 'B' from the branch data.

$$B = \frac{1}{x_{ij}} \quad (1)$$

Where x_{ij} is the reactance of the line between i, j buses.

5. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.
6. Calculate the inverse of the resultant matrix.
7. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as 'X'.
8. Calculate the LODF $d_{l,k}$ of any line l when a line k is outaged in the system given by,

$$d_{l,k} = \frac{\frac{x_k}{x_l} (X_{in} - X_{jn} - X_{im} + X_{jm})}{x_k - (X_{nn} + X_{mm} - 2X_{nm})} \quad (2)$$

9. Repeat the process for all the lines in the system.
10. Assign the impact on the line to the 'from' and 'to' buses of the line and cumulatively add together the impact on each bus and rank the buses according to their sensitivities.

Thus the LODF of all the lines in the system is calculated when a single line is outaged in the system. Sensitive buses thus obtained will be used for taking corrective and preventive action in the system.

4.2. Algorithm for MLODF

1. Input the branch data and bus data for the test case.
2. Calculate the number of buses and number of branches from the data.
3. Define the slack bus and its corresponding number.
4. Calculate the susceptance matrix 'B' from the branch data.

$$B = \frac{1}{x_{ij}} \quad (3)$$

Where x_{ij} is the reactance of the line between i, j buses.

5. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.
6. Calculate the inverse of the resultant matrix.
7. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as 'X'.
8. Find the Power Transfer Distribution Factor (PTDF) for all the lines when the power system is operating normally as well as when a single line is out in the system using the formula,

$$PTDF_{ijmn} = \frac{X_{im} - X_{jm} - X_{in} + X_{jn}}{x_{ij}} \quad (4)$$

Where, m is the seller bus and n is the buyer bus.

x_{ij} is the reactance of the transmission line connecting zone i and j .

x_{im} Entry in the i th row and the m th column of the bus reactance matrix X .

9. Calculate the matrices a, b, c, d , and e mentioned below.

$$10. \text{ Define } \alpha = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Where α is the matrix with ptdf's of lines when their corresponding lines are outaged.

11. Calculate the MLODF of the remaining lines in the system. $MLODF = \text{inv}(I - \alpha)^*e$

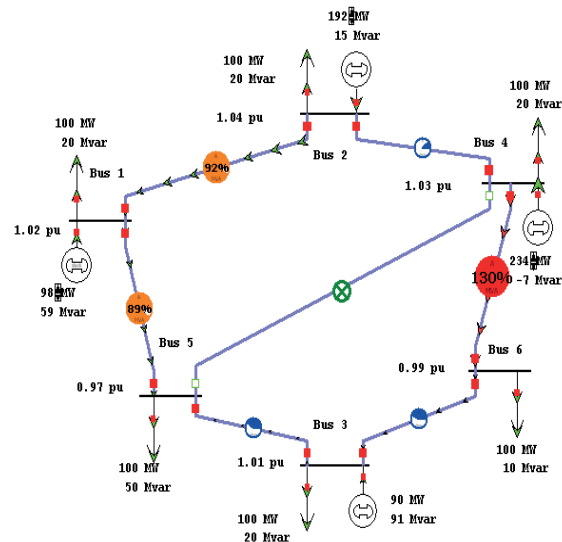
12. Attribute the MLODF to the corresponding buses attached to the lines and cumulatively add them together to get the MLOBSF for all the buses in the system.

13. Rank the buses according to their sensitivities.

This process is repeated for all the buses in the system and the impact on each bus is cumulatively added together to get the list of buses and their sensitivities.

5. Simulation Results and Discussion

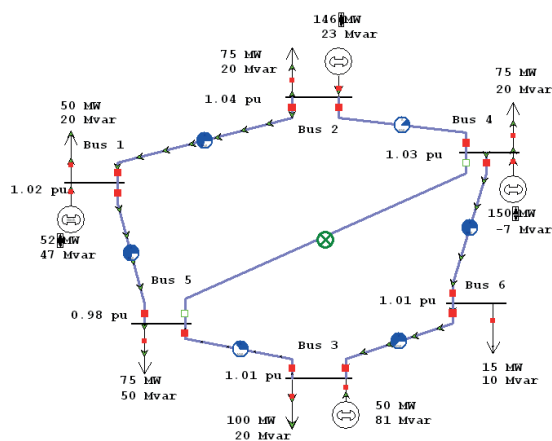
This section deals with implementing the MLODF algorithm for N-1, N-2, N-3 and N-4 line contingencies on the test cases using Power World simulator and results are also given. The three test cases used are 6 bus system, 30 and 37 bus test case systems. Results and corrective and preventive actions taken to solve the violations are given below.



Figure(1) N-1 Line contingency on 6bus system

Figure(1) shows the N-1 line contingency on the six bus test case system. The line outaged is 6(5-4), as shown in figure(1). The power flows on rest of the lines after the outage are also shown by the arrows in the figure. Some of the lines have been carrying the power more than the limit. Action should be taken to solve these MVA violations. The MLODF program for the above contingency gives the ranking of sensitive buses, where action needs to be taken.



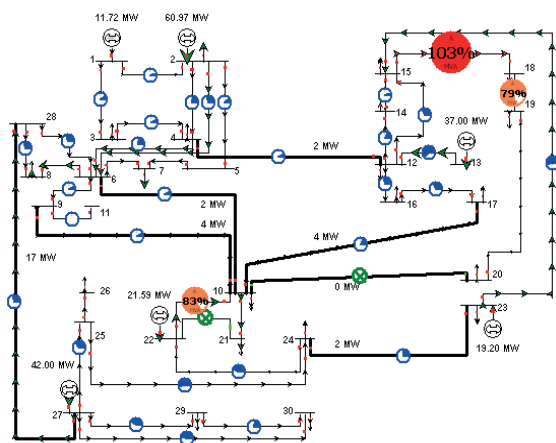


Figure(2) N-1 line violations solved after action taken on 6bus system.

After reducing the generation at bus(4) to 150MW and also shedding the load at buses(2,4,5) to 75MW and at bus(6) to 15MW, at bus(1) to 50MW the MW on the lines have come back to within its operational limits. As seen in table(1), the MVA limit of the lines and all line flows are within operating limits.

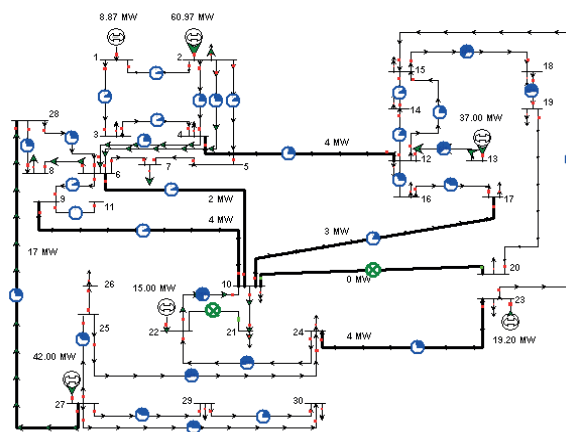
Table(1) Violated lines for N-1 contingency 6 bus system

Line No.	Base case(MVA)	Post Outage(MVA)	After remedial action on sensitive buses
4-6	96.7	129.8	75.3
2-1	61.1	92.1	70.6
1-5	52.0	88.6	72.5



Figure(3) N-2 Line contingency on IEEE30bus system

Figure(3) shows the N-2 line contingency on IEEE30 bus system. The lines outaged are 19(10-20) and 32(22-21) as shown in figure(3). The power flows on rest of the lines after the outage are also shown by the arrows. Some of the lines have been carrying the power more than the limit. Action should be taken to solve these MVA violations. The MLODF program for the above contingency gives the ranking of sensitive buses, where action needs to be taken.

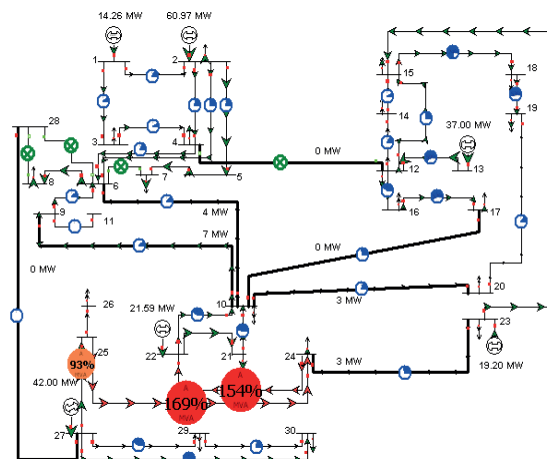


Figure(4) N-2 line violations solved after remedial action taken on 30bus system

After reducing the generation at the top most sensitive bus(22) and also shedding load at the top three sensitive buses(10,18,19) the MW on the lines have come back to within its operational limits. As seen in the table(2), MVA limit of the lines and all line flows are within operating limits.

Table(2) Violated lines for N-2 contingency on 30 bus system

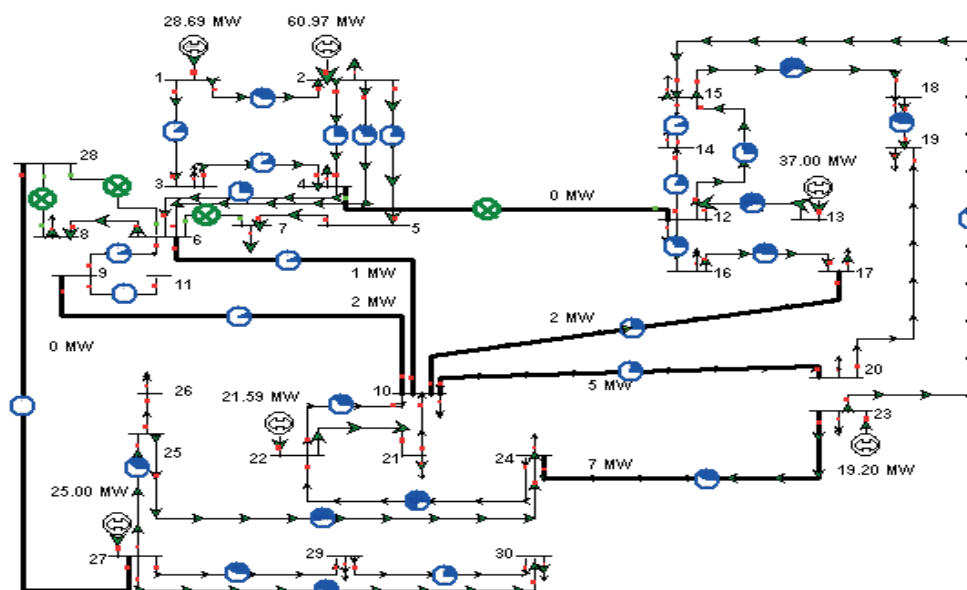
Line No.	Base case(MVA)	Post Outage(MVA)	After remedial action on sensitive buses
15-18	9.2	16.4	10.6
22-10	9.8	25.7	23.1
18-19	5.8	12.6	8.8



Figure(5) N-4 Line contingency on IEEE30bus system

Figure(5) shows the N-4 line contingency on IEEE30 bus system. The lines outaged are 8(4-12), 10(7-6), 14(28-6) and 15(28-8) as shown in figure(5). The power flows on rest of the lines after the outage are also shown by the arrows. Some of the lines have been carrying the power more than the limit. Action should be taken to solve these MVA violations. The MLODF program for the above contingency gives the ranking of sensitive buses, where action needs to be taken.





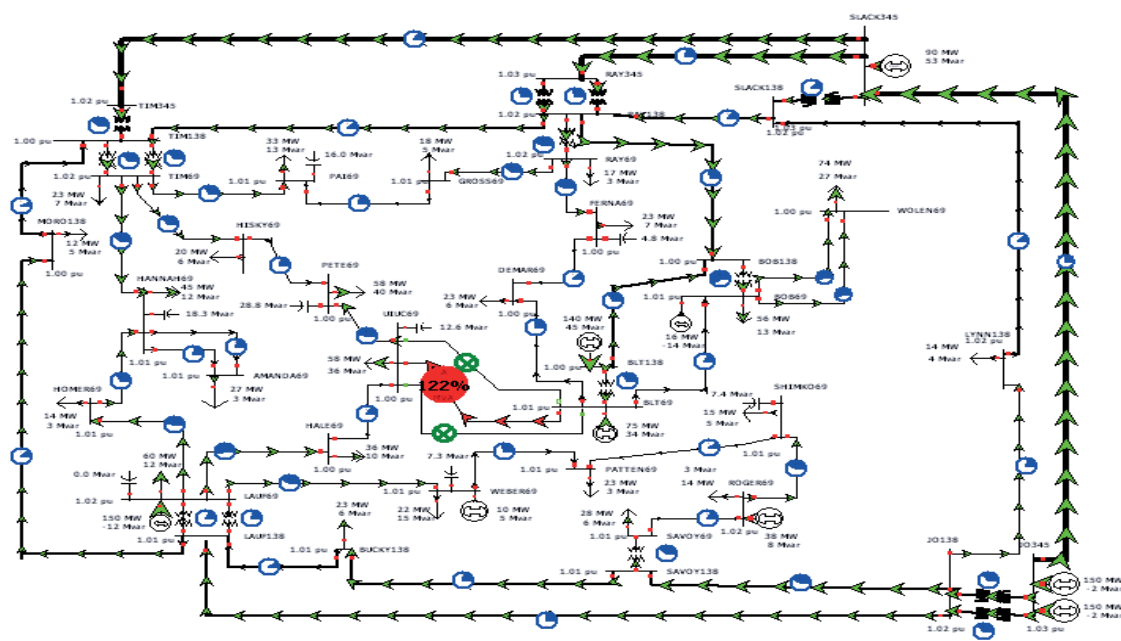
Figure(6) N-4 line violations solved after remedial action taken on 30bus system

After reducing the generation at the top most sensitive bus(27) the MW on the lines have come back to within its operational limits. As seen in the table(3), MVA

limit of the lines and all line flows are within operating limits.

Table(3) Violated lines for N-4 contingency on 30 bus system

Line No.	Base case(MVA)	Post Outage(MVA)	After remedial action on sensitive buses
25-24	9.5	27.0	8.9
24-22	11.0	24.6	11.5
27-25	12.3	29.7	11.8

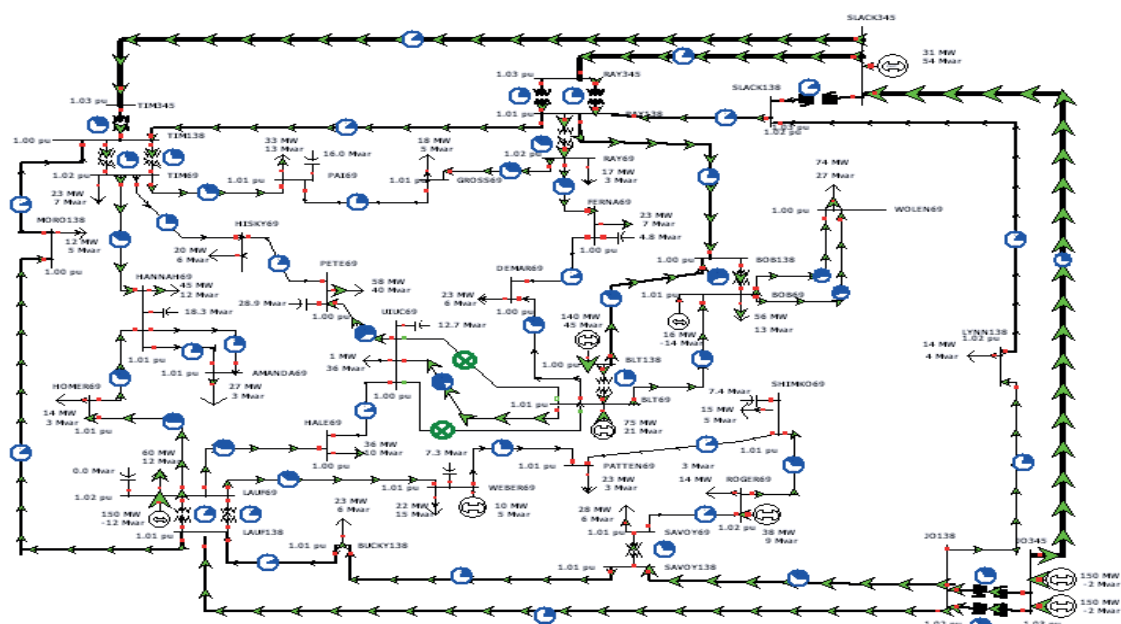


Figure(7) N-2 Line contingency on 37bus system

Figure(7) shows the N-2 line contingency on 37 bus system. The lines outaged are 20(15-54) and 22(15-54) as shown in figure(7). The power flows on rest of the lines after the outage are also shown by the arrows. Some of the lines have been carrying the power more

than the limit. Action should be taken to solve these MVA violations. The MLODF program for the above contingency gives the ranking of sensitive buses, where action needs to be taken.





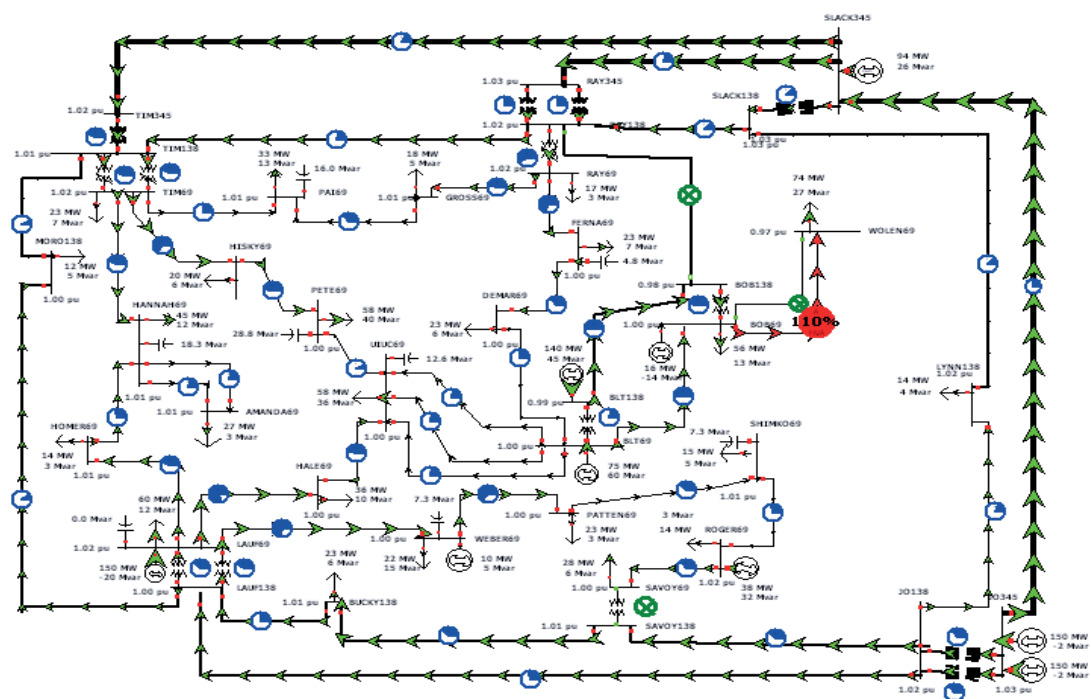
Figure(8) N-2 line violations solved after action taken on 37bus system

After shedding load at the top most sensitive bus(15) the MW on the lines have come back to within its operational limits. As seen in the table(4), MVA limit

of the lines and all line flows are within operating limits.

Table(4) Violated lines for N-2 contingency on 37 bus system

Line No.	Base case(MVA)	Post Outage(MVA)	After remedial action on sensitive bus
21(15-54)	32.7	94.1	61.4

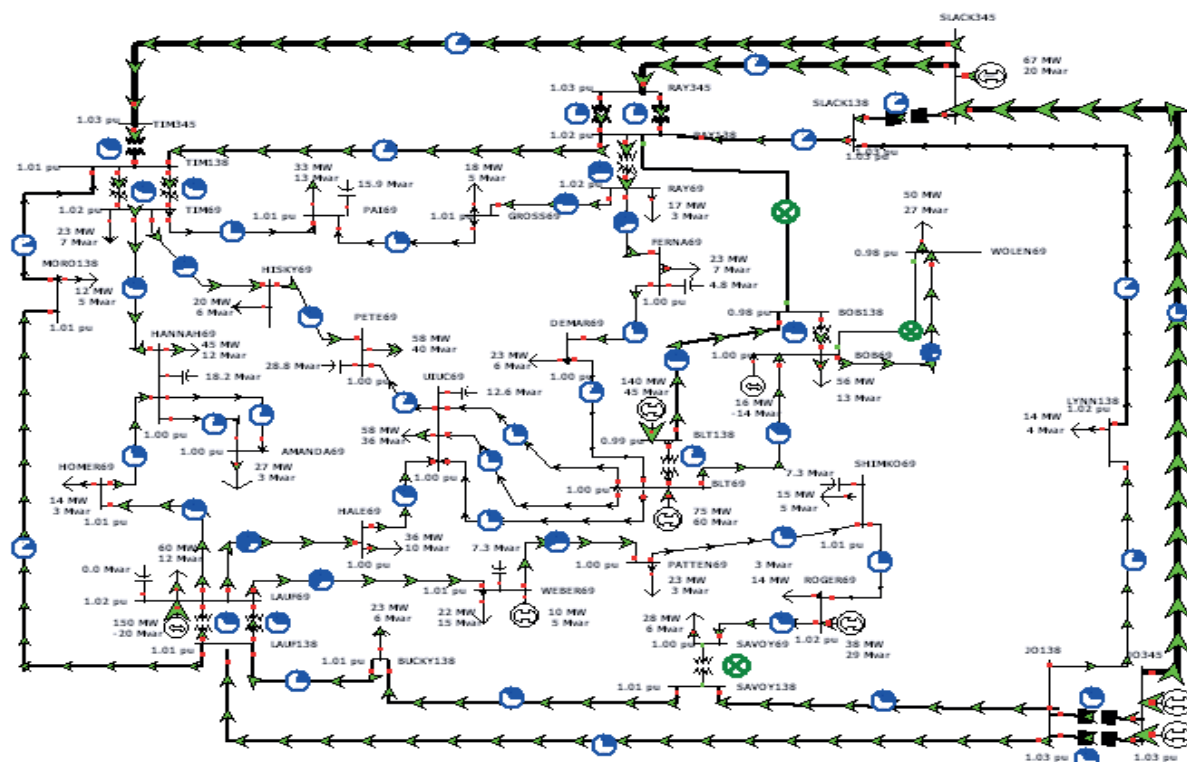


Figure(9) N-3 Line contingency on 37bus system

Figure (9) shows the N-3 line contingency on 37 bus system. The lines outaged are 30(21-48), 43(33-32) and 50(39-47) as shown in figure(9). The power flows on rest of the lines after the outage are also shown by the more than the limit. Action should be taken to solve these

MVA violations. The MLODF program for the above contingency gives the ranking of sensitive buses, where action needs to be taken. arrows. Some of the lines have been carrying the power





Figure(10) N-3 line violations solved after action taken on 37bus system

After shedding load at the top most sensitive bus(21) the MW on the lines have come back to within its

operational limits. As seen in the table(5), MVA limit of the lines and all line flows are within operating limits.

Table(5) Violated lines for N-3 contingency on 37 bus system

Line No.	Base case(MVA)	Post Outage(MVA)	After remedial action on sensitive bus
31(21-48)	39.5	79.1	56.7

6. Conclusion

The present day power systems are prone to multiple contingencies being highly interconnected and complex. Study of multiple contingencies and associated remedial actions has received less attention by the power industry. This paper summarizes the work developed to deal with the impact of multiple contingencies in the power system networks. Remedial control actions are required to be planned by operating personnel to avoid system entering into emergency state under major outages. Although there are several remedial action schemes suggested, for the single (N-1) contingency cases, very few efforts have been made in developing the schemes for multiple contingencies. This paper deals with developing corrective actions for higher order contingencies. In interconnected practical power system, higher order contingencies may happen more frequently. Therefore, it is necessary that the utilities be prepared for these contingencies to prevent loss of service.

In this paper, Multiple Line Outage Distribution Factor (MLODF) algorithm is developed to determine corrective actions under multiple contingencies, in order to remove major system violations caused by these contingencies. The above algorithm is quite fast and can be used for real

time applications for taking corrective actions. This algorithm is implemented on three test systems, a six bus system test system, a thirty bus test system and a 37 bus test system. The algorithm is successfully implemented on these test systems for N-2 and N-3 contingencies (line outages) using Power World simulator. The corrective actions effectively removed the limit violations in the system. The results obtained through the proposed algorithm are found to be quite accurate and thus, this work provides new tool for developing remedial control actions for higher order contingencies.

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Reduction of Common Mode Voltage using Space Vector Based PWM Techniques for Induction Motor Drives

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Abstract

In conventional space vector pulse width modulation (CSVPWM), the complexity involved in calculation of sector and angle information is more. Moreover common mode voltage (CMV) is more due to usage of zero voltage vectors V_0 and V_7 . To reduce CMV and complexity involved in CSVPWM algorithm, this paper presents a simplified active zero state PWM algorithms (AZPWM) using the concept of imaginary switching times in which actual switching times are calculated from the sampled phase voltages. In the proposed approach, for the reduction of CMV instead of using zero voltage vectors two active opposite voltage vectors with equal time duration are utilized with two adjacent active voltage vectors to compose required reference voltage vector. Though these AZPWM methods reduce the computational burden involved in calculation, they still suffer from steady state ripples in torque, flux and current. To reduce the ripples in steady state, a hybrid PWM (HPWM) technique is developed in which stator flux ripple analysis is done for all the AZPWM sequences. To validate the proposed PWM algorithms, numerical simulation studies have been carried out v/f controlled induction motor drive using MATLAB-Simulink and results are presented and compared

Keywords : *imaginary switching times, induction motor drives, PWM inverter, SVPWM, CMV variations*

1. Nomenclature

L_m, L_r, L_s	Self and mutual inductances, ohms
T_e	Electromagnetic torque, N-M
P	Number of poles
λ_s	Stator flux linkage space vector, V-S
λ_r	Rotor flux linkage space vector, V-S
T_s	Sampling time period, S
T_1, T_2	Active vector switching times, S
T_z	Zero vector switching time, S
M	Modulation index
V_{no}	Common mode voltage, V

2. Introduction

Induction motors were widely used in industries due to its robustness, low cost and high reliability [1]. Among the PWM-voltage source inverter (VSI) drives induction motor drives with cage type machines have found wide range of applications. These motors can be fed from VSI and used as variable speed drives. Recent advances in fast switching semi conductor technology have led to new generations of fast-acting power semi conductor switches like IGBTs, IGCTs which increases the switching frequency of inverter control there by improving the dynamic performance of pwm inverter fed ac motor drives. Moreover, this rapid development has created several unexpected problems such as conducted EMI, shaft voltages, bearing currents, breakdown of motor insulation [2]-[3]. The direct cause of above mentioned problems presented is common mode voltage which is generated in the inverter itself. Many studies for reducing the common mode voltage have been progressed. These studies however focused on the design of common mode choke, 4-phase inverter and various types of active filters [4]-[7]. Since these methods require additional hardware and has drawbacks of increase in inverter weight and volume which are unavoidable.

One of the most widely used strategies for generating inverter output voltage is to employ a PWM technique which varies duty cycle of inverter switches. Conventional space vector PWM (SVPWM) is a widely used PWM strategy which has the advantages of low harmonic distortion in the output current and suitable for digital implementation. In this approach, two active voltage vectors and two zero voltage vectors are utilized to match the reference volt-seconds. This technique also generates high level CMV variations due to the presence of zero voltage vectors [8]-[10]. To reduce the complexity involved in conventional SVPWM algorithm, space vector approach using the concept of imaginary switching times is proposed in [11]-[12]. For the reduction of CMV variations performance analysis of AZPWM and Remote State PWM (RSPWM) methods



are considered with standard PWM methods employing open loop v/f control algorithm. Though these methods reduce CMV variations, they still require angle information for calculation of switching times [13]. So, these methods increase the complexity of PWM algorithm. A new HPWM technique for the reduction of stator flux ripple is proposed in [14]-[16] but still they suffer from high CMV due to usage of zero voltage vectors.

The main objective of this paper is to develop a hybrid PWM technique using different AZPWM sequences based on the concept of imaginary switching times for reduced current ripple and CMV variations.

The paper is organized as follows: section 3 introduces conventional SVPWM. Section 4 explains the proposed PWM techniques. Section 5 explains the ripple analysis of the proposed PWM techniques. Section 6 introduces the proposed Hybrid PWM method. Section 7 presents the simulation results of proposed PWM techniques along with HPWM method. Conclusions are given in Section 8.

3. Conventional SVPWM (SVPWM)

With a three phase, two-level voltage source inverters (VSI), there are eight possible switching states. In case of the switching states V_0 and V_7 , all the three poles are connected to the same dc bus, effectively shorting the induction motor and resulting in no transfer of power between the dc bus and induction motor. These two states are called 'zero voltage vectors' or 'zero states'. In case of the other switching states, power gets transferred between the dc bus and induction motor as shown in Fig.1

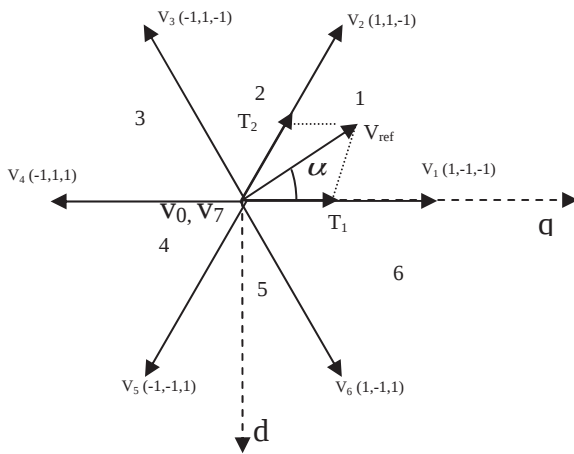


Fig. 1 Construction of reference voltage vector

In SVPWM technique, actual switching times can be produced by the recombination of effective voltage vectors using the information of the reference voltage vectors location. Suppose assume that sample lies in first sector, V_{ref} at α angle can be generated by using two zero voltage vectors V_0 and V_7 in combination with two adjacent active voltage vectors V_1 and V_2 for time durations T_1 , T_2 and T_z respectively within the sampling time period T_s . The actual switching times can be obtained as given in (1)-(3). Construction of reference voltage vector is shown in Fig 2. In SVPWM algorithm the zero state time T_z is divided equally between V_0 and V_7 .

$$T_1 = M * \frac{3}{\pi} * \frac{\sin(60^\circ - \alpha)}{\sin(60^\circ)} * T_s \quad (1)$$

$$T_2 = M * \frac{3}{\pi} * \frac{\sin \alpha}{\sin 60^\circ} * T_s \quad (2)$$

$$T_z = T_s - (T_1 + T_2) \quad (3)$$

Where M is the modulation index and given

$$\text{by } M = \frac{\pi * V_{ref}}{2 * V_{dc}} .$$

As SVPWM algorithm requires the information regarding sector identification and angle the complexity involved in calculations is more. Moreover SVPWM uses zero voltage vectors with two adjacent vectors for composing the reference voltage vector which increases the CMV.

Common Mode Voltage (CMV)

According to the switching states of the inverter, the CMV can be expressed as

$$V_{no} = \frac{(V_{ao} + V_{bo} + V_{co})}{3} \quad (4)$$

Where V_{ao} , V_{bo} , V_{co} are the inverter pole voltages.

CMV changes instantaneously when the drive is fed from an inverter. Table -I indicates for different switching states. From the table it can be observed that CMV changes from one switching state of the inverter to the other, if only even or only odd vectors are used there will be no change in V_{com} , if a transition from an even voltage vector to an odd voltage vector occurs, a V_{com} variation of $V_{dc}/3$ is generated, if a transition from an even (odd) voltage vector to the zero (seventh) voltage vector occurs a V_{com} of $2V_{dc}/3$ is generated which is a worst case. So, in order to avoid CMV variations of the drive eliminate the usage of zero voltage vectors in the proposed methods.

Table – I: CMV variations for different Inverter Switching States

State	V_{ao}	V_{bo}	V_{co}	V_{com}
V_0	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$
V_1	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_2	$V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/6$
V_3	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/2$	$-V_{dc}/6$
V_4	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_5	$-V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}/6$
V_6	$V_{dc}/2$	$-V_{dc}/2$	$V_{dc}/2$	$V_{dc}/6$
V_7	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$

4. Proposed PWM Algorithms

In the Proposed approach, different AZPWM sequences are considered for the reduction of CMV, in which instead of using zero voltage vectors, active voltage vectors are used to compose the reference vector. Moreover to reduce complexity in calculations of CSVPWM, in the Proposed PWM algorithms the active vector switching times are calculated by using imaginary switching times. The actual switching times can be obtained directly, if the equations are simplified in terms of instantaneous phase voltages corresponding to the reference voltage vector [11]. They are as follows

$$T_1 = T_{as} - T_{bs} \text{ and } T_2 = T_{bs} - T_{cs} \quad (5)$$



Where $T_{as} = \frac{V_{as}}{V_{dc}} T_s$, $T_{bs} = \frac{V_{bs}}{V_{dc}} T_s$, and $T_{cs} = \frac{V_{cs}}{V_{dc}} T_s$ are the three imaginary switching times.

The switching sequences in each sector for the proposed PWM techniques are shown in Table-II. In Active Zero State PWM (AZPWM) methods, instead of zero voltage vectors V_0 and V_7 two active opposite voltage vectors are used with two adjacent voltage vectors to compose the reference vector. Any one of the three pairs V_1 - V_4 , V_2 - V_5 , V_3 - V_6 can be used. From Table-II in sector-I, consider AZPWM1 and AZPWM4 sequences, two active opposite voltage vectors V_3 - V_6 are used with the two adjacent voltage vectors V_1 - V_2 to compose the reference vector. AZPWM1 method involves 60° jump in the output voltage vectors during commutation from

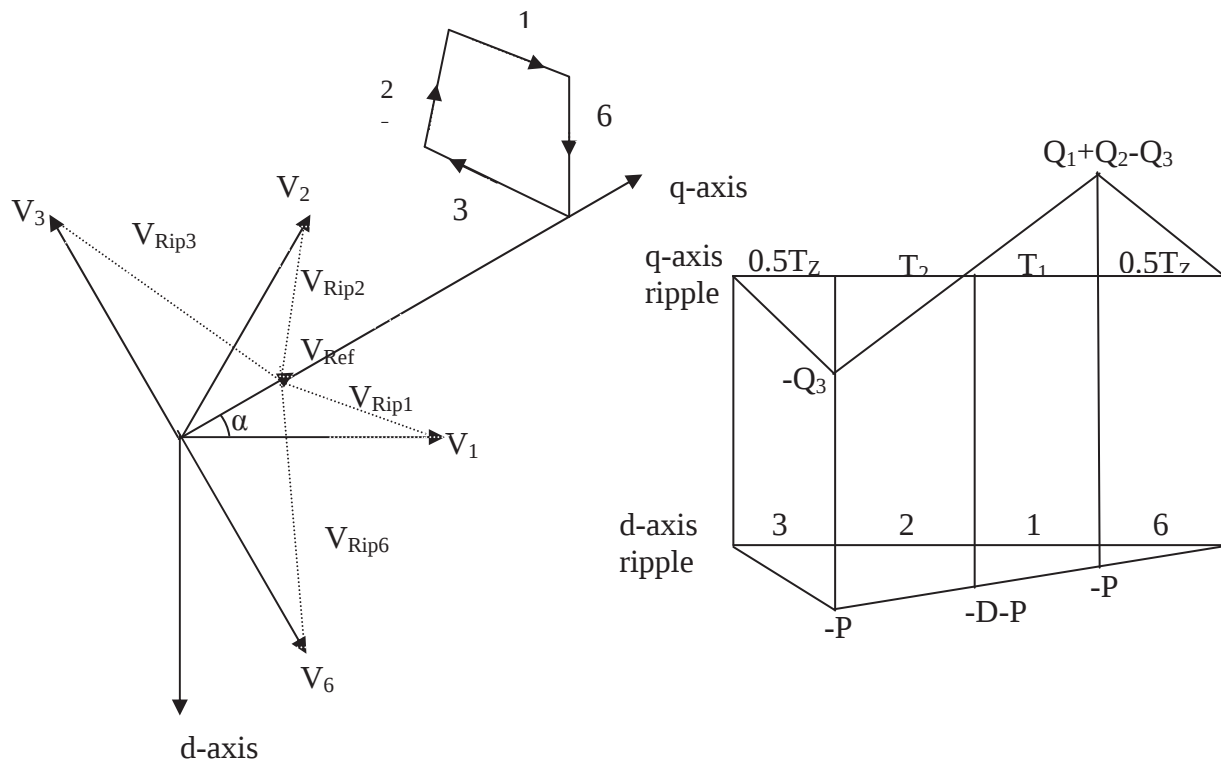
adjacent active voltage vectors (V_1, V_2) to the active opposite voltage vectors (V_3, V_6), whereas AZPWM4 method involves 120° jumps in the output voltage vectors during commutation from adjacent active vectors to the active opposite voltage vectors V_3 and V_6 acting as zero vectors. All the three AZPWM methods have CMV of $+V_{dc}/6$ or $-V_{dc}/6$ whereas SVPWM has as high as $+V_{dc}/2$ or $-V_{dc}/2$. Though these methods reduce CMV they suffer from steady state ripples.

It is worthwhile to note that the proposed AZPWM sequences (AZPWM1, AZPWM3) along with SVPWM involve only three switching's to generate a sample while AZPWM4 sequence involve five switching's per sample. In order to keep the average switching frequency constant the sub cycle duration for AZPWM4 sequence is $5/3$ of the other sequences.

Table II: Switching sequences of different PWM algorithms

PWM METHOD	S-I	S-II	S-III	S-IV	S-V	S-VI
AZPWM1	3216-6123	1234-4321	5432-2345	3456-6543	1654-4561	5612-2165
AZPWM3	2215-5122	6233-3326	4431-1344	2455-5542	6653-3566	4611-1164
AZPWM4	6213-3126	4231-1324	2435-5342	6453-3546	4651-1564	2615-5162

5. Expressions for RMS flux Ripple



(a) AZPWM1



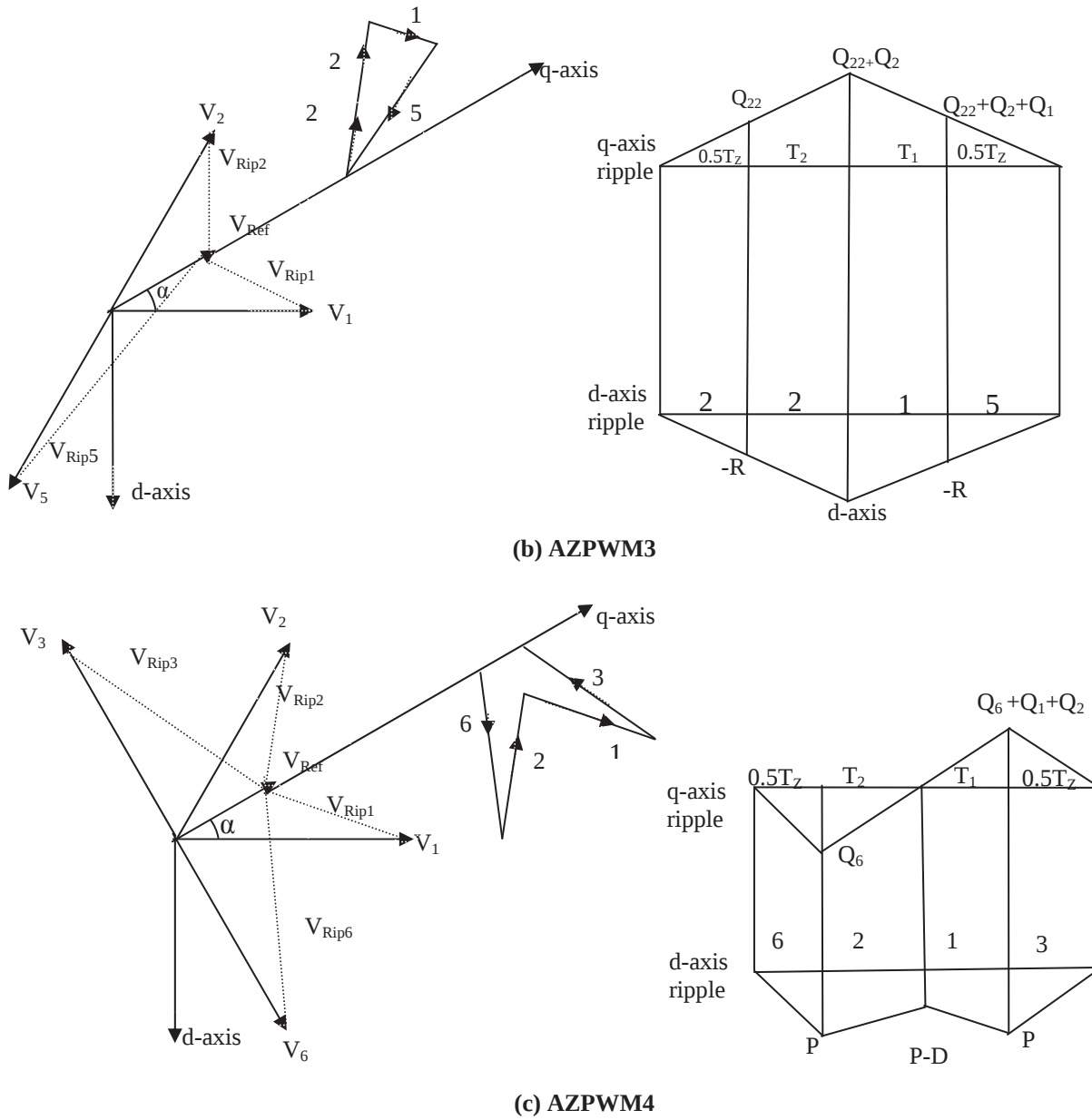


Figure.2 Variations of stator flux ripple vector over a sampling period and its corresponding d- axis and q-axis components of AZPWM sequences

The rms stator flux ripple is a measure of current ripple in the line current. The time integral of error between the applied voltage vector and the reference voltage vector is defined as the stator flux ripple vector. The instantaneous voltage ripple vectors in the synchronously revolving d-q reference frame corresponding to the active vector 1, active vector 2 and the active zero vectors are shown in Fig.2. The error volt-seconds corresponding to ripple voltage vectors can be developed as given in [14]. For the AZPWM sequences the d-axis stator flux ripple components are given in terms of D, R and P and q-axis stator flux ripple components are given in terms of Q_1 , Q_2 , Q_3 , Q_{22} , Q_3 , Q_5 , Q_6 which are defined as (6)-(11).

AZPWM1, AZPWM4

$$V_{rip1}T_1 = \frac{2}{3}V_{dc} \sin \alpha T_1 + j\left(\frac{2}{3}V_{dc} \cos \alpha - V_{ref}\right)T_1 \quad (6)$$

$$= D + jQ_1$$

$$V_{rip2}T_2 = \frac{2}{3}V_{dc} \sin(60^\circ - \alpha)T_2 + j\left(\frac{2}{3}V_{dc} \cos(60^\circ - \alpha) - V_{ref}\right)T_2 \quad (7)$$

$$= -D + jQ_2$$

$$V_{rip3}T_{\frac{Z}{2}} = -\frac{2}{3}V_{dc} \sin(60^\circ + \alpha)T_{\frac{Z}{2}} - j\left(\frac{2}{3}V_{dc} \cos(60^\circ + \alpha) + V_{ref}\right)T_{\frac{Z}{2}}$$

$$= -P - jQ_3 \quad (8)$$

$$V_{rip6}T_{\frac{Z}{2}} = \frac{2}{3}V_{dc} \sin(60^\circ + \alpha)T_{\frac{Z}{2}} + j\left(-\frac{2}{3}V_{dc} \cos(60^\circ + \alpha) + V_{ref}\right)T_{\frac{Z}{2}}$$

$$= P + jQ_6 \quad (9)$$

AZPWM3

$$V_{rip22}T_{\frac{Z}{2}} = -\frac{2}{3}V_{dc} \sin(60^\circ - \alpha)T_{\frac{Z}{2}} + j\left(\frac{2}{3}V_{dc} \cos(60^\circ - \alpha) - V_{ref}\right)T_{\frac{Z}{2}}$$

$$= -R + jQ_{22} \quad (10)$$

$$V_{rip5}T_{\frac{Z}{2}} = \frac{2}{3}V_{dc} \sin(60^\circ - \alpha)T_{\frac{Z}{2}} + j\left(-\frac{2}{3}V_{dc} \cos(60^\circ - \alpha) + V_{ref}\right)T_{\frac{Z}{2}}$$



$$= R + jQ_5 \quad (11)$$

The terms given in (6)-(11) contain angle 'α', this has to be eliminated to reduce the complexity in calculations. From (1)-(3) the values of $\sin\alpha$, $\cos\alpha$, $\cos(60^\circ - \alpha)$, $\sin(60^\circ - \alpha)$, can be obtained as given in (12)-(17).

$$\sin(\alpha) = \frac{\pi * T_2}{2 * \sqrt{3} * M * T_s} \quad (12)$$

$$\cos(\alpha) = \frac{\pi * (T_1 + 0.5 * T_2)}{3 * M * T_s} \quad (13)$$

$$\sin(60^\circ - \alpha) = \frac{\pi * T_1}{2 * \sqrt{3} * M * T_s} \quad (14)$$

$$\cos(60^\circ - \alpha) = \frac{\pi * (T_2 + 0.5 * T_1)}{3 * M * T_s} \quad (15)$$

$$\sin(60^\circ + \alpha) = \frac{\pi * (T_1 + T_2)}{2 * \sqrt{3} * M * T_s} \quad (16)$$

$$\cos(60^\circ + \alpha) = \frac{\pi * (T_1 - T_2)}{2 * 3 * M * T_s} \quad (17)$$

By substituting these values in (6)-(11) the values of Q_1 , Q_2 , Q_{22} , Q_3 , Q_5 , Q_6 , P , R and D can be obtained in terms of switching times, without angle which are required for estimation of stator flux ripple. Over a sampling interval, the mean square stator flux ripple for AZPWM sequences can be calculated as

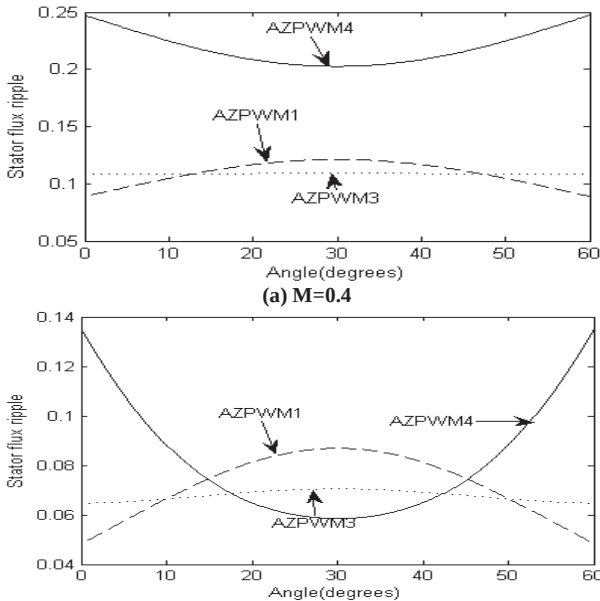
$$F_{3216}^2 = \frac{1}{3} (0.5 * Q_3^2) \frac{T_z}{T_s} + \frac{1}{3} (Q_1 + Q_2 - Q_3)^2 \frac{T_1}{T_s} + \frac{1}{3} (P^2) \frac{T_z}{T_s} + \frac{1}{3} (3P^2 + D^2 + 3PD) \frac{(T_1 + T_2)}{T_s} + \frac{1}{3} (Q_3^2) \frac{T_2}{T_s} + \frac{1}{3} (0.5 * (Q_1 - Q_3 + Q_2)^2) \frac{T_z}{T_s} \quad (18)$$

$$F_{2215}^2 = \frac{1}{3} (0.5 * Q_{22}^2) \frac{T_z}{T_s} + \frac{1}{3} (.3 * Q_{22}^2 + Q_2^2 + 3Q_{22}Q_2) \frac{T_2}{T_s} + \frac{1}{3} (R^2) \frac{T_z}{T_s} + \frac{1}{3} (3R^2 + D^2 + 3RD) \frac{(T_1 + T_2)}{T_s} + \frac{1}{3} (0.5 * (Q_{22} + Q_1 + Q_2)^2) \frac{T_z}{T_s} + \frac{1}{3} (3 * (Q_{22} + Q_2)^2 + 3 * (Q_{22} + Q_2) * Q_1 + Q_1^2) \frac{T_1}{T_s} \quad (19)$$

$$F_{6213}^2 = \frac{1}{3} (0.5 * Q_6^2) \frac{T_z}{T_s} + \frac{1}{3} (Q_1 + Q_2 + Q_6)^2 \frac{T_1}{T_s} + \frac{1}{3} (P^2) \frac{T_z}{T_s} + \frac{1}{3} (3P^2 + D^2 - 3PD) \frac{(T_1 + T_2)}{T_s} + \frac{1}{3} (Q_6^2) \frac{T_2}{T_s} + \frac{1}{3} (0.5 * (Q_1 + Q_6 + Q_2)^2) \frac{T_z}{T_s} \quad (20)$$

6. Proposed hybrid PWM method

As AZPWM methods suffer from steady state ripples, in this paper a new hybrid PWM technique is proposed for v/f controlled induction motor drive for reduced current ripple. The rms flux ripple characteristics obtained from (18)-(20) for the proposed AZPWM algorithms are compared with respect to each other and the corresponding sequence which gives the minimum mean square ripple than other sequences for a given modulation index is then obtained. From Fig. 3(a)-3(c) it can be observed that at lower modulation indices ($M=0.4$) AZPWM3 exhibits superior performance characteristics over other sequences and at higher modulation indices ($M=0.61$ and $M=0.8$) AZPWM4 exhibits superior performance characteristics over other sequences.



(b) $M=0.61$

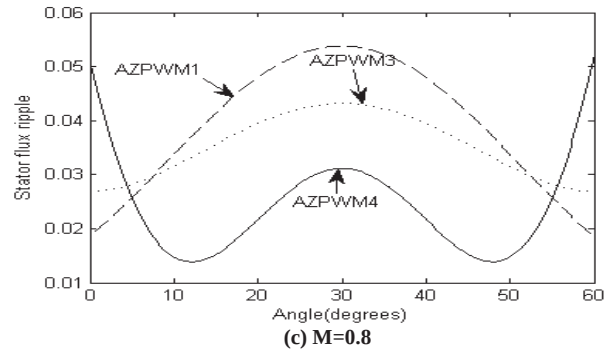


Figure . 3 Variations of rms stator flux ripple at various modulation indices

7. Simulation Results and Discussion

To validate the proposed PWM algorithms, numerical simulation studies have been carried out on V/f controlled induction motor drive by using Matlab /Simulink at no-load. For the simulation, the reference flux is taken as 1wb and starting torque is limited to 45 N-m. For the simulation studies, a 3-phase, 400V, 4 kW, 4-pole, 50 Hz, 1470 rpm induction motor has considered. The parameters of the given induction motor are as follows: $R_s=1.57\text{ohm}$, $R_r=1.21\text{ohm}$, $L_m=0.165\text{H}$, $L_s=0.17\text{H}$, $L_r=0.17\text{H}$ and $J=0.089\text{ Kg} \cdot \text{m}^2$. Simulation for the proposed methods under various conditions such as steady state, starting transients, CMV and THD of stator current is done. In this paper the Simulation results for CMV variations and THD of stator current of proposed methods are given in Figure. 4- Figure.11. From Figure.4, Figure.6 Figure.8 and Figure.10 it can be observed that the harmonic spectrum of stator current of HPWM algorithm is less when compared with AZPWM methods. From Figure.5, Figure.7 Figure.9 and Figure.11 it can be



observed that the CMV variations of HPWM algorithm varies from $+V_{dc}/6$ to $-V_{dc}/6$ as with AZPWM methods.

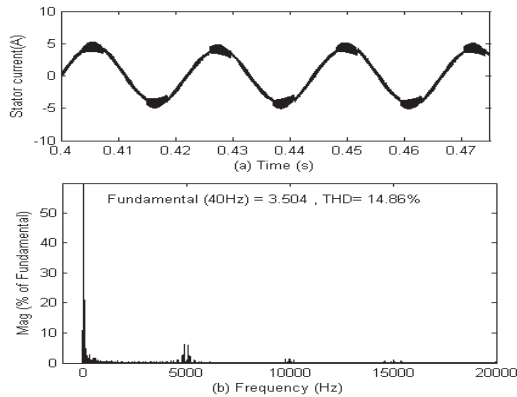


Figure .4 Measured no-load current and harmonic distortion in current of AZPWM1 at M=0.8

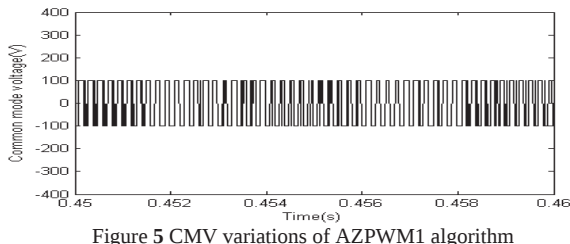


Figure 5 CMV variations of AZPWM1 algorithm

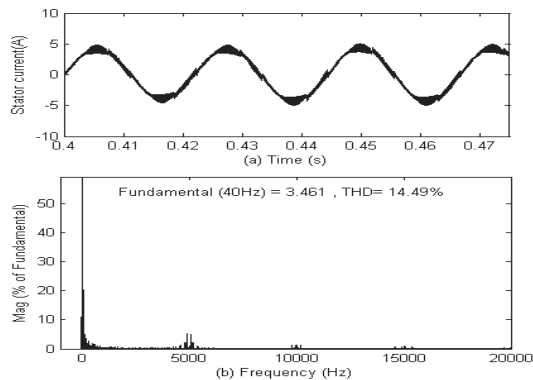


Figure .6 Measured no-load current and harmonic distortion in current of AZPWM3 at M=0.8

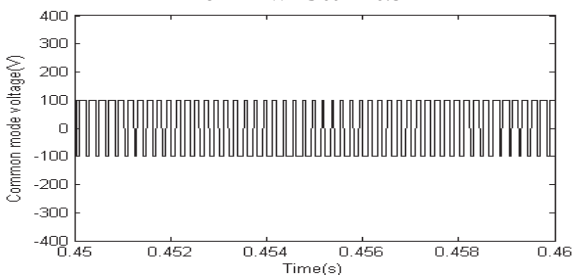


Figure 7 CMV variations of AZPWM3 algorithm

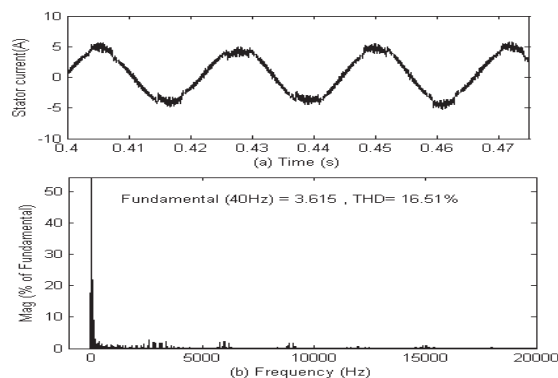


Figure .8 Measured no-load current and harmonic distortion in current of AZPWM4 at M=0.8

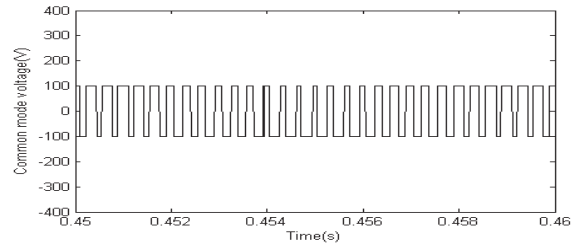


Figure 9 CMV variations of AZPWM4 at M=0.8

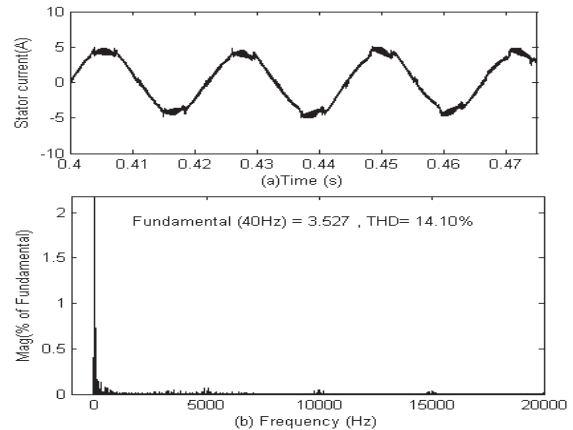


Figure .10 Measured no-load current and harmonic distortion in current of HPWM at M=0.8

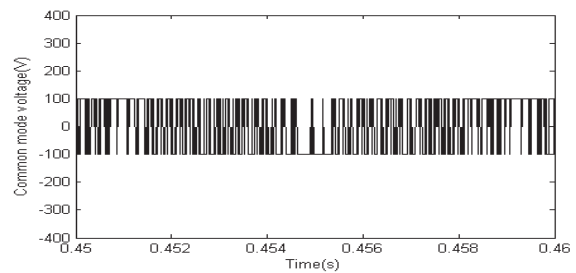


Figure 11 CMV variations of HPWM algorithm

8. Conclusions

SVPWM is the most popular PWM technique because of numerous advantages. Though SVPWM is popular it suffers from the drawbacks like computational burden and high CMV variations. To reduce the CMV variations, simple and novel space vector based PWM algorithms are proposed using the concept of imaginary switching times. In the proposed PWM algorithms, only active voltage vectors are used in each sector to compose the reference voltage vector. Moreover the proposed AZPWM methods though reduce the CMV but have high stator flux, torque, current ripples. So, in order to reduce the ripples hybrid PWM algorithm is developed and proposed. From the simulation results, it can be observed that the hybrid PWM has less stator flux, torque, current ripples when compared with AZPWM methods. Moreover, the proposed PWM methods reduce the CMV due to application of active voltage vectors.

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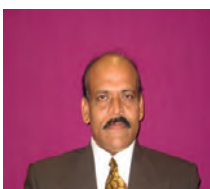
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Influence of FACTS Devices on Congestion Management in Deregulated Power System

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Abstract

Deregulation of electric industry has a direct impact on the increasing number of transactions. This lowers the available margin and leads to the increased congestion of transmission lines. Thus the system becomes more vulnerable to collapse. Analyzing the system security and congestion, and determining their effects on pricing becomes more important than ever in the deregulated environment. This paper proposes a method for the placement of Flexible AC Transmission System devices in deregulated power system to reduce congestion. Locational marginal price is used to study the effect of congestion in the pricing model. The proposed method is based on Locational Marginal Price differences of Optimal Power Flow to find the optimal location of Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase Angle Regulator (TCPAR) devices. The overall objective function can be either to minimize the congestion rent or to maximize the social welfare. The proposed method is tested on an IEEE 24rts system, an IEEE 57 bus system and an IEEE 118 bus system. Results shows that the proposed method for TCSC is capable for reducing the congestion rent and for TCPAR is capable for maximizing the social welfare.¹

Keywords: Congestion, OPF, TCSC, TCPAR, LMP

1. Introduction

In a modern power system, the transmission system must be operated flexible in a safe boundary. As electric power industry around the world is undergoing shift towards deregulation, it is expected to leads to more competition and would increase the number of transactions to sell and purchase electricity using transmission line. Besides, more network congestions are expected in the competitive electricity market [1], operating the

transmission system in reliable boundary will be more important problem than now.

In the deregulated electricity market, electricity prices are determined using the marginal cost calculated from OPF[2]. As the existing electric transmission systems are utilized to transport more energy, congestions are more likely to occur at different locations throughout the network, resulting in reduced power flow between the areas in proximity of congestion.

This limits the amount of energy transaction between those areas, inducing the price differences in the corresponding zones. In presence of congestion in the transmission system, prices will differ from that of the unconstrained price. In fact, congestions can produce significant price variations between different areas of a network and can result in security concerns. The locational marginal pricing (LMP) methodology [3] has been the dominant approach in power markets to calculate electricity prices and to manage transmission congestion.

Increasing attention has been given to application of FACTS devices in power systems in the recent past, as these devices are proven to be a promising solution for various power system problems. One pertinent issue related to FACTS application is the selection of appropriate location. Proper location is a key to maximize the benefits of the expensive FACTS devices. FACTS devices like TCSC and TCPAR are considered as such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, along with many other benefits. Various issues associated with the use of FACTS devices are proper location, appropriate size and setting, cost, modeling and controller interactions. This paper deals with the location aspect of the series FACTS devices, especially to manage congestion in the deregulated electricity markets.

This paper presents the new methodology for proper location of FACTS devices for congestion management in the deregulated power systems. These methods make use of economic signal given as LMP [4]. The LMP based market is gaining popularity in recent years and is

¹ This study has been implemented on Powerworld simulator at Gokaraju Rangaraju Institute of Engineering and Technology.



the preferred way of pricing energy and managing congestion. The proposed method is used to locate TCSC and TCPAR.

2. Modelling of FACTS devices

Power system is to be continuously expanded and upgraded to cater the ever-growing power demand. Due to limited energy resources, time and capital required, the present trend is looking for the new techniques for improving the power system performance. A new technology consisting of FACTS controllers has the ability to control the interrelated parameters that govern the operation of transmission system.

There is a better utilization of existing transmission system assets. Building new transmission lines to meet the increasing electricity demand is always limited economically and by environmental constraints and FACTS devices meet these requirements using the existing transmission systems. Increase in dynamic and transient grid stability and reduction of loop flows is achievable as FACTS devices can stabilize transmission systems with higher energy transfer capability and reduction in risks of line trips. In fact FACTS devices help to distribute electricity more economically through better utilization of existing installations thereby reducing the need for additional transmission lines.

Modelling of TCSC: Transmission lines are represented by lumped π equivalent parameters. The series compensator TCSC is simply a static capacitor with impedance $-jX_c$ [5]. The controllable reactance X_c is directly used as the control variable in the power flow equations

Figure1 shows a transmission line incorporating a TCSC.

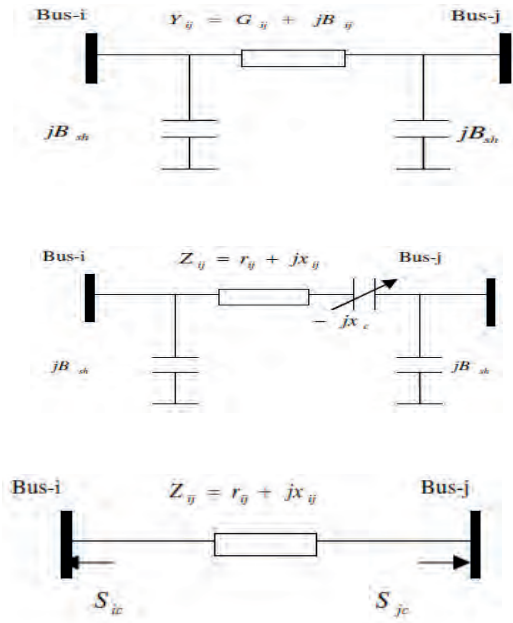


Figure 1(a) Simple Transmission line
1(b) Model of Transmission line with TCSC
1(c) Injected Model of TCSC.

The Figure1.a shows a simple transmission line represented by its lumped π equivalent parameters connected between bus-i and bus-j. Let complex voltage at bus-i and bus-j are $V_i \angle \delta_i$ and $V_j \angle \delta_j$ respectively.

The real and reactive power flow from bus-i to bus-j can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \quad (1)$$

$$Q_{ij} = -V_i^2 (B_{ij} + B_{sh}) - V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \quad (2)$$

$$\text{Where } \delta_{ij} = \delta_i - \delta_j$$

Similarly the real and reactive power flow from bus-j to bus-i can be written as

$$P_{ji} = V_j^2 G_{ij} - V_i V_j [G_{ij} \cos(\delta_{ij}) - B_{ij} \sin(\delta_{ij})] \quad (3)$$

$$Q_{ji} = -V_j^2 (B_{ij} + B_{sh}) + V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})] \quad (4)$$

The active and reactive power losses in the line are

$$P_L = P_{ij} + P_{ji} = G_{ij} (V_i^2 + V_j^2) - 2V_i V_j G_{ij} \cos \delta_{ij} \quad (5)$$

$$Q_L = Q_{ij} + Q_{ji} = -(V_i^2 + V_j^2)(B_{ij} + B_{sh}) + 2V_i V_j G_{ij} \cos \delta_{ij} \quad (6)$$

$$\text{Where } G_{ij} = \frac{r_{ij}}{r_{ij}^2 + x_{ij}^2} \text{ and } B_{ij} = \frac{-x_{ij}}{r_{ij}^2 + x_{ij}^2}$$

The model of transmission line with a TCSC connected between bus-i and bus-j is shown in Figure1.b. During the steady state the TCSC can be considered as a static reactance $-jX_c$. The real and reactive power flow from

bus-i to bus-j and from bus-j to bus-i of a line having series impedance and a series reactance are

$$P'_{ij} = V_i^2 G'_{ij} - V_i V_j [G'_{ij} \cos(\delta_{ij}) + B'_{ij} \sin(\delta_{ij})] \quad (7)$$

$$Q'_{ij} = -V_i^2 (B'_{ij} + B_{sh}) - V_i V_j [G'_{ij} \sin(\delta_{ij}) - B'_{ij} \cos(\delta_{ij})] \quad (8)$$

$$P'_{ji} = V_j^2 G'_{ij} - V_i V_j [G'_{ij} \cos(\delta_{ij}) - B'_{ij} \sin(\delta_{ij})] \quad (9)$$

$$Q'_{ji} = -V_j^2 (B'_{ij} + B_{sh}) + V_i V_j [G'_{ij} \sin(\delta_{ij}) + B'_{ij} \cos(\delta_{ij})] \quad (10)$$

The active and reactive power losses in the line with TCSC are

$$P'_L = P'_{ij} + P'_{ji} = G'_{ij} (V_i^2 + V_j^2) - 2V_i V_j G'_{ij} \cos \delta_{ij} \quad (11)$$

$$Q'_L = Q'_{ij} + Q'_{ji} = -(V_i^2 + V_j^2)(B'_{ij} + B_{sh}) + 2V_i V_j G'_{ij} \cos \delta_{ij} \quad (12)$$

$$\text{Where } G'_{ij} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2} \text{ and}$$

$$B'_{ij} = \frac{-(x_{ij} - x_c)}{r_{ij}^2 + (x_{ij} - x_c)^2}$$

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line as shown in Figure1.c. The real and reactive power injections at bus-i and bus-j can be expressed as

$$P'_i = V_i^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos(\delta_{ij}) + \Delta B_{ij} \sin(\delta_{ij})] \quad (13)$$

$$Q'_i = -V_i^2 (\Delta B_{ij} + B_{sh}) - V_i V_j [\Delta G_{ij} \sin(\delta_{ij}) - \Delta B_{ij} \cos(\delta_{ij})] \quad (14)$$

Similarly, the real and reactive power injections at bus-j and bus-i can be expressed as

$$P'_j = V_j^2 \Delta G_{ij} - V_i V_j [\Delta G_{ij} \cos(\delta_{ij}) - \Delta B_{ij} \sin(\delta_{ij})] \quad (15)$$

$$Q'_j = -V_j^2 (\Delta B_{ij} + B_{sh}) + V_i V_j [\Delta G_{ij} \sin(\delta_{ij}) + \Delta B_{ij} \cos(\delta_{ij})] \quad (16)$$

$$\text{Where } \Delta G_{ij} = \frac{r_{ij} x_c (x_c - 2x_{ij})}{(r_{ij}^2 + x_{ij}^2) \{r_{ij}^2 + (x_{ij} - x_c)^2\}}$$

$$\Delta B_{ij} = \frac{-x_c (x_c x_{ij} - x_{ij}^2 + r_{ij}^2)}{(r_{ij}^2 + x_{ij}^2) \{r_{ij}^2 + (x_{ij} - x_c)^2\}}$$

Modelling of TCPAR: In a thyristor-controlled phase angle regulator, the phase shift is achieved by introducing a variable voltage component in perpendicular to the phase voltage of the line. The static model of a TCPAR



having a complex tap ratio of $1:a\angle\alpha$ and a transmission line between bus i and bus j is shown in Fig2.a

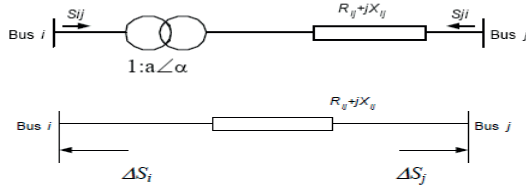


Figure 2(a) Model of TCPAR
2(b) Injected model of TCPAR

The real and reactive power flows from bus i to bus j can be expressed as

$$P_{ij} = a^2 V_i^2 G_{ij} - a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) - a V_i V_j B_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (17)$$

$$Q_{ij} = -a^2 V_i^2 B_{ij} + a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) - a V_i V_j G_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (18)$$

Similarly, real and reactive power flows from bus j to bus i can be written as

$$P_{ji} = V_j^2 G_{ij} - a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) + a V_i V_j B_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (19)$$

$$Q_{ji} = -V_j^2 B_{ij} - a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) + a V_i V_j G_{ij} \sin(\delta_i - \delta_j + \alpha) \quad (20)$$

The real and reactive power loss in the line having a TCPAR can be expressed as

$$P_L = a^2 V_i^2 G_{ij} + V_j^2 G_{ij} - 2a V_i V_j G_{ij} \cos(\delta_i - \delta_j + \alpha) \quad (21)$$

$$Q_L = -a^2 V_i^2 B_{ij} - V_j^2 B_{ij} + a V_i V_j B_{ij} \cos(\delta_i - \delta_j + \alpha) \quad (22)$$

The power injected at the receiving and sending ends of the line as shown in Figure 2.b.

The real and reactive power injections at bus- i and bus- j can be expressed as

$$P_i' = -a^2 V_i^2 G_{ij} - a V_i V_j [G_{ij} \sin(\delta_{ij}) - B_{ij} \cos(\delta_{ij})] \quad (23)$$

$$Q_i' = a^2 V_i^2 B_{ij} + a V_i V_j [G_{ij} \cos(\delta_{ij}) + B_{ij} \sin(\delta_{ij})] \quad (24)$$

Similarly, the real and reactive power injections at bus- j and bus- i can be expressed as

$$P_j' = -a V_i V_j [G_{ij} \sin(\delta_{ij}) + B_{ij} \cos(\delta_{ij})] \quad (25)$$

$$Q_j' = -a V_i V_j [G_{ij} \cos(\delta_{ij}) - B_{ij} \sin(\delta_{ij})] \quad (26)$$

3. OPF formulation

Optimal Power flow (OPF) has been used in this work to calculate generation dispatch and load schedules to obtain LMPs and to manage congestion in the transmission systems [6,7]. It is based on the bids submitted by the generators and loads and the network data. The overall objective function is to maximize the social welfare.

The problem is stated mathematically as

$$\text{Min} \left(\sum_{i=1}^{N_G} C_i(P_{Gi}) \right) \quad (27)$$

Subject to

Power balance equation:

$$P_i(\theta, V) - P_{Gi} + P_{Di} = 0, \text{ for any node } i$$

$$Q_i(\theta, V) - Q_{Gi} + Q_{Di} = 0, \text{ for any node } i$$

If TCSC or TCPAR is located between buses i and j , the power balance equations in nodes i and j are given by

$$P_i(\theta, V) - P_{Gi} + P_{Di} + P_i' = 0, \text{ for node } i$$

$$Q_i(\theta, V) - Q_{Gi} + Q_{Di} + Q_i' = 0, \text{ for node } i$$

$$P_j(\theta, V) - P_{Gj} + P_{Dj} + P_j' = 0, \text{ for node } j$$

$$Q_j(\theta, V) - Q_{Gj} + Q_{Dj} + Q_j' = 0, \text{ for node } j$$

Apparent line flow limit:

$$S_{ij}(\theta, V) \leq S_{ij}^{\max}$$

Power generation limit:

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}$$

Bus voltage and angle limits:

$$V_i^{\min} \leq V_i \leq V_i^{\max}$$

$$\theta_i^{\min} \leq \theta_i \leq \theta_i^{\max}$$

TCSC reactance limits:

$$x_c^{\min} \leq x_c \leq x_c^{\max}$$

TCPAR phase angle limits:

$$\alpha^{\min} \leq \alpha \leq \alpha^{\max}$$

Where N_G is the number of generators, $C_i(P_{Gi})$ is the bid curve of i^{th} generator, $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum and maximum active power generation limits of a generator at bus i , $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the minimum and maximum reactive power generation limits of a generator at bus i , $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum voltage limits at bus i , S_{ij} is the apparent power flow in transmission line connected between lines i and j , and $S_{ij}^{\max}$ is the maximum limit. $x_c^{\min}$ and $x_c^{\max}$ are the minimum and maximum limits of TCSC reactance. $\alpha^{\min}$ and $\alpha^{\max}$ are the minimum and maximum limits of TCPAR Phase angle.

Solution Technique: The augmented objective function of the above OPF problem augmenting all the constraints for TCSC is expressed as

$$\begin{aligned} L = & \left(\sum_{i=1}^{N_G} C_i(P_{Gi}) \right) + \sum_{i=1}^N \lambda_{Pi} (P_i - P_{Gi} + P_{Di} + P_i') + \\ & \sum_{i=1}^N \lambda_{Qi} (Q_i - Q_{Gi} + Q_{Di} + Q_i') + \sum_{ij} \mu_{Lij} (S_{ij} - S_{ij}^{\max}) \\ & + \sum_{i=1}^{N_G} \mu_{P_{Gi}}^{\min} (P_{Gi}^{\min} - P_{Gi}) + \sum_{i=1}^{N_G} \mu_{P_{Gi}}^{\max} (P_{Gi} - P_{Gi}^{\max}) + \sum_{i=1}^{N_G} \mu_{Q_{Gi}}^{\min} (Q_{Gi}^{\min} - Q_{Gi}) \\ & + \sum_{i=1}^{N_G} \mu_{Q_{Gi}}^{\max} (Q_{Gi} - Q_{Gi}^{\max}) + \sum_{i=1}^N \mu_{V_i}^{\min} (V_i^{\min} - V_i) + \sum_{i=1}^{N_G} \mu_{V_i}^{\max} (V_i - V_i^{\max}) \\ & + \mu_{x_c}^{\min} (x_c^{\min} - x_c) + \mu_{x_c}^{\max} (x_c - x_c^{\max}) \end{aligned} \quad (28)$$

The augmented objective function of the above OPF problem augmenting all the constraints for TCPAR is expressed as

$$\begin{aligned} L = & \left(\sum_{i=1}^{N_G} C_i(P_{Gi}) \right) + \sum_{i=1}^N \lambda_{Pi} (P_i - P_{Gi} + P_{Di} + P_i') + \\ & \sum_{i=1}^N \lambda_{Qi} (Q_i - Q_{Gi} + Q_{Di} + Q_i') + \sum_{ij} \mu_{Lij} (S_{ij} - S_{ij}^{\max}) \\ & + \sum_{i=1}^{N_G} \mu_{P_{Gi}}^{\min} (P_{Gi}^{\min} - P_{Gi}) + \sum_{i=1}^{N_G} \mu_{P_{Gi}}^{\max} (P_{Gi} - P_{Gi}^{\max}) + \sum_{i=1}^{N_G} \mu_{Q_{Gi}}^{\min} (Q_{Gi}^{\min} - Q_{Gi}) \\ & + \sum_{i=1}^{N_G} \mu_{Q_{Gi}}^{\max} (Q_{Gi} - Q_{Gi}^{\max}) + \sum_{i=1}^N \mu_{V_i}^{\min} (V_i^{\min} - V_i) + \sum_{i=1}^{N_G} \mu_{V_i}^{\max} (V_i - V_i^{\max}) \\ & + \mu_{\alpha}^{\min} (\alpha^{\min} - \alpha) + \mu_{\alpha}^{\max} (\alpha - \alpha^{\max}) \end{aligned} \quad (29)$$

Where, λ_P and λ_Q are the Lagrange multipliers associated with the equality constraints and $\mu_L, \mu_{P_{Gi}}^{\min}, \mu_{P_{Gi}}^{\max}, \mu_{Q_{Gi}}^{\min}, \mu_{Q_{Gi}}^{\max}, \mu_{V_i}^{\min}, \mu_{V_i}^{\max}, \mu_{x_c}^{\min}, \mu_{x_c}^{\max}, \mu_{\alpha}^{\min}, \mu_{\alpha}^{\max}$ are the



Lagrange multipliers associated with the inequality constraints.

In Eqs [28,29], the important one is Lagrange Multiplier λ_p associated with real power balance equations. It is actually the spot price or nodal price or LMP and form of pricing energy in OPF based deregulated market. LMP is generally composed of three

Components, a marginal energy component, a marginal loss component and a congestion component. The decomposition of nodal spot price obtained from OPF into three components. For a case of real power spot price at bus i , considering all constraints in the OPF, the decomposition of the nodal spot price in to three components is given by

$$\rho_i = \lambda_e + \lambda \frac{\partial P_L}{\partial P_i} + \sum_{ij=1}^{N_L} \mu_{L_{ij}} \frac{\partial P_{ij}}{\partial P_i} \quad (30)$$

$$\rho_i = \lambda_e + \lambda_{L,i} + \lambda_{C,i} \quad (31)$$

Similarly, for bus j , the spot price (LMP) can be written similar to (10):

$$\rho_j = \lambda_e + \lambda_{L,j} + \lambda_{C,j} \quad (32)$$

Taking the spot price difference between two buses i and j , we get:

$$\Delta \rho_{ij} = (\lambda_{L,i} - \lambda_{L,j}) + (\lambda_{C,i} - \lambda_{C,j}) \quad (33)$$

Eq. (33) shows that the nodal price difference between any two buses depend on the marginal losses and the congestion throughout the network. The price differential, by definition gives the congestion rent (i.e. merchandise surplus). The surplus arises because generators are compensated by LMP at the respective generator buses (which are generally low) and loads are charged by LMP at the respective load buses (which are generally high).

The total congestion rent is calculated as

$$TCC = \sum_{ij=1}^{N_L} \Delta \rho_{ij} P_{ij} \quad (34)$$

LMP Difference Method: The main concept behind the LMP difference method is to make use of the economic signal given as LMP to select the best location for FACTS device to manage congestion. It is motivated from the fact that LMP contains significant information regarding level of congestion in the system [8]. LMP is composed of three components, an energy component, a loss component and a congestion component. For a meshed system, loss component is generally small. Hence, the difference in LMP between two buses gives direct hint regarding the level of congestion in that line. Since, LMP difference is highest for the congested/overloaded lines (i.e. line operating at limit) and overloaded lines are not always the best locations for placement of series FACTS devices, a neighborhood search method is required which will be taken care by formation of priority list.

Hence, in this method, a priority list is formed based on the magnitude of the difference in LMPs. Priority list will essentially capture the congested lines as well as the neighborhood lines that are linked to the congested lines through which the power can be diverted when FACTS is placed. The number of lines to be considered for priority list depends on the size of the system, and there is no

hard and fast rule. However, it should be at least greater than the number of congested lines in the system.

The advantage of the proposed method is that it helps to form the priority list for TCSC and TCPAR location directly from the OPF results and avoid excessive computation. Only few line in the priority list need to be examined in detail to assess the best location. Since, these methods make use of economic signal given as LMP; it is easily applicable in the deregulated power systems.

Calculation procedure of the proposed methods is summarized in the following steps:

- Step 1: Run the base case OPF to calculate the LMP at all buses and the power flow across all line sections.
- Step 2: Calculate the absolute value of the LMP difference and arrange in descending order of magnitude to form priority table (for LMP difference method).
- Step 3: For each line in the priority list, run OPF with FACTS device in that line and calculate the total congestion rent and the value of the objective function (i.e. total generation cost or the total social welfare).
- Step 4: The best location of FACTS device is the one where by placing FACTS device gives the minimum congestion cost or minimum value of the objective function (i.e. minimum generation cost or maximum social welfare).

4. Results and Discussions

The Proposed method for optimal placement of TCSC and TCPAR for congestion management is tested on IEEE 24 rts system, IEEE 57 bus system, IEEE 118 bus system. The network and load data for these systems are taken from [9]. The calculation of LMP is carried out using Power world Simulator8.0.

For IEEE 24 rts system, the priority list is formed with 8 candidate lines, while for IEEE 57-bus system and IEEE 118 bus system, the priority list is formed consisting of 10 candidate locations.

IEEE 24 rts system:

For IEEE 24 rts system, there are 11 generators, 38 line sections, 17 loads as shown in Figure 3. All bus voltages are taken as 1.0 p.u.

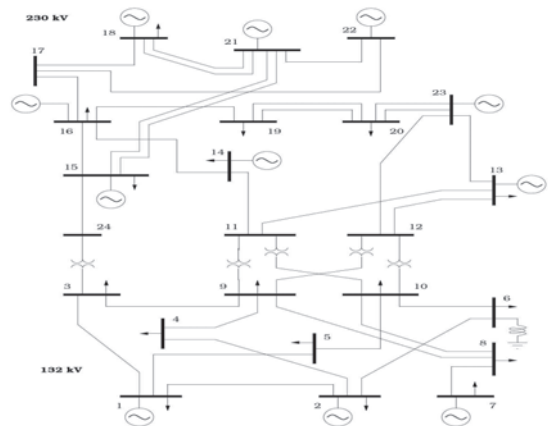


Figure 3 IEEE 24 rts system



Table 1: Priority Table based on LMP difference for IEEE 24 rts system

Priority	LMP Difference	Priority location
1	2.17	13-23
2	2.11	2-6
3	1.79	8-10
4	1.71	14-16
5	1.62	17-22
6	1.57	2-4
7	1.41	15-24
8	1.4	7-8

Table 2: Priority Table based on Congestion rent with TCSC for IEEE 24 rts system

Priority	Total Congestion rent(\$/hr)	Priority location
1	4601.113	7-8
2	4625.848	15-24
3	4659.776	2-4
4	4662.549	14-16
5	4715.66	2-6
6	4756.89	8-10
7	5804.923	17-22
8	9914.61	13-23

Table 3: Priority Table based on Generation cost with TCSC for IEEE 24 rts system

Priority	Total Generation Cost(\$/hr)	Priority location
1	63560.64	7-8
2	63654.35	15-24
3	63685.2	2-4
4	63969.4	8-10
5	64029.04	14-16
6	66455.2	2-6
7	69030.82	17-22
8	102884.7	13-23

Table 1 shows the Priority table based on LMP differences for 24 rts system. The top 8 candidate locations are selected. For each line in the priority table, TCSC is located in series with the line with 70% of the reactance of the line and total congestion rent and total generation cost is calculated and tabulated in the Table 2, 3. By observing Table 2, the first best location for TCSC to minimize total congestion rent is line 7-8. By observing Table 3, the first location for TCSC to minimize the total generation cost is line 7-8. From the priority tables, it is observed that line 7-8 is the best location for locating TCSC to minimize total congestion rent and total generation cost.

Table 4: Priority Table based on Congestion rent with TCPAR for IEEE 24 rts system

Priority	Total Congestion rent(\$/hr)	Priority location
1	4608.377	17-22
2	4608.73	15-24
3	4609.655	13-23
4	4610.504	14-16
5	4610.819	7-8
6	4611.112	8-10
7	4612.099	2-4
8	4612.298	2-6

For each line in the priority table based on LMP Difference, TCPAR is located in the line with a phase shift angle of 4.5° and total congestion rent and total generation cost is calculated and tabulated in the Table 4,5. By observing table 4, the first best location for

TCPAR to minimize total congestion rent is line 17-22. By observing table 5, the first location for TCPAR to minimize the total generation cost is line 7-8. By comparing the total congestion rent and total generation cost by placing TCSC and TCPAR, it is observed that the minimum generation cost with TCSC is 63560.64(\$/hr) and minimum generation cost with TCPAR is 63551.6(\$/hr). It is observed that the total generation cost can be reduced by placing of TCPAR than by placing of TCSC.

Table 5: Priority Table based on Generation cost with TCPAR for IEEE 24 rts system

Priority	Total Generation Cost(\$/hr)	Priority location
1	63551.6	7-8
2	63558.33	8-10
3	63563.75	15-24
4	63565.71	2-6
5	63572.57	17-22
6	63573.3	14-16
7	63575.48	13-23
8	63582.04	2-4

IEEE 57 bus system:

For IEEE 57 bus system, there are 7 generators, 80 line sections, 42 loads as shown in Figure 4.

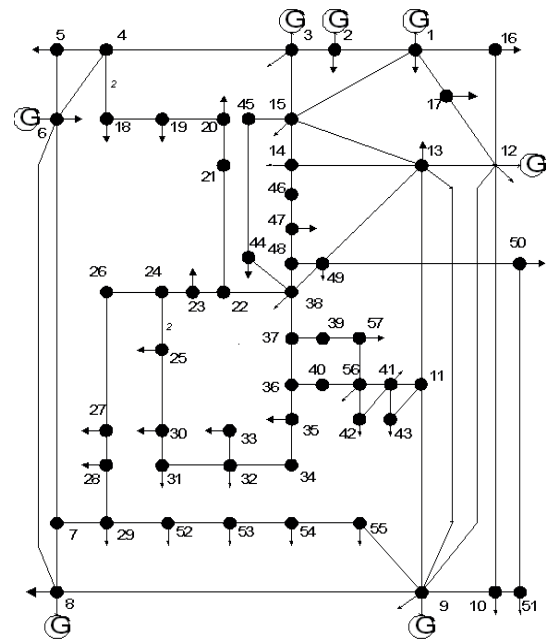


Figure 4 IEEE 57 bus system

Table 6: Priority Table based on LMP difference for IEEE 57 bus system

Priority	LMP Difference	Priority location
1	3.54	56-41
2	2.61	29-52
3	2.58	26-27
4	2.5	41-42
5	2.37	18-19
6	1.77	8-9
7	1.72	9-13
8	1.71	30-31
9	1.69	44-45
10	1.67	25-30

Table 6 shows the Priority table based on LMP differences for 57 bus system. The top 10 candidate



locations are selected. For each line in the priority table, TCSC is located in series with the line with 70% of the reactance of the line and total congestion rent and total generation cost is calculated and tabulated in the Table 7, 8. By observing Table 7, the first best location for TCSC to minimize total congestion rent is line 8-9. By observing Table 8, the first location for TCSC to minimize the total generation cost is line 25-30.

Table 7: Priority Table based on Congestion rent with TCSC for IEEE 57 bus system

Priority	Total Congestion rent(\$/hr)	Priority location
1	1489.243	8-9
2	1509.572	29-52
3	1517.207	26-27
4	1518.334	25-30
5	1518.645	30-31
6	1518.943	41-42
7	1519.32	18-19
8	1519.405	56-41
9	1523.563	44-45
10	1599.416	9-13

Table 8: Priority Table based on Generation cost with TCSC for IEEE 57 bus system

Priority	Total Generation Cost(\$/hr)	Priority location
1	42021.14	25-30
2	42022.22	30-31
3	42030.08	41-42
4	42033.25	18-19
5	42039.42	29-52
6	42059.82	56-41
7	42078.3	26-27
8	42079.35	44-45
9	42226.48	8-9
10	42365.96	9-13

Table 9: Priority Table based on Congestion rent with TCPAR for IEEE 57 bus system

Priority	Total Congestion rent(\$/hr)	Priority location
1	1511.738	8-9
2	1514.709	26-27
3	1517.928	56-41
4	1518.48	29-52
5	1518.578	9-13
6	1518.596	44-45
7	1519.534	30-31
8	1519.534	25-30
9	1521.033	18-19
10	1523.756	41-42

Table 10: Priority Table based on Generation cost with TCPAR for IEEE 57 bus system

Priority	Total Generation Cost(\$/hr)	Priority location
1	42020.17	25-30
2	42027.18	30-31
3	42027.51	18-19
4	42036.14	29-52
5	42039.94	41-42
6	42042.92	56-41
7	42052.17	44-45
8	42058.08	9-13
9	42062.21	26-27
10	42076.77	8-9

For each line in the priority table based on LMP Difference, TCPAR is located in the line with a phase shift angle of 4.5° and total congestion rent and total generation cost is calculated and tabulated in the Table

9,10. By observing Table 9, the first best location for TCPAR to minimize total congestion rent is line 8-9. By observing Table 10, the first location for TCPAR to minimize the total generation cost is line 25-30. By comparing the total congestion rent and total generation cost by placing TCSC and TCPAR, it is observed that the minimum generation cost with TCSC is 42021.14 (\$/hr) and minimum generation cost with TCPAR is 42020.17 (\$/hr). It is observed that the total generation cost can be reduced by placing of TCPAR than by placing of TCSC.

IEEE 118bus system:

For IEEE 118 bus system, there are 186 line sections, 54 generators.

Table 11: Priority Table based on LMP difference for IEEE 118 bus system

Priority	LMP Difference	Priority location
1	2.67	100-104
2	2.04	45-49
3	1.97	80-96
4	1.85	47-69
5	1.7	100-103
6	1.64	38-65
7	1.6	49-51
8	1.53	103-105
9	1.5	26-30
10	1.47	49-69

Table 11 shows the Priority table based on LMP differences for 118 bus system. The top 10 candidate locations are selected. For each line in the priority table, TCSC is located in series with the line with 70% of the reactance of the line and total congestion rent and total generation cost is calculated and tabulated in the Table 12, 13. By observing Table 12, the first best location for TCSC to minimize total congestion rent is line 100-103. By observing Table 13, the first location for TCSC to minimize the total generation cost is line 26-30.

Table 12: Priority Table based on Congestion rent with TCSC for IEEE 118 bus system

Priority	Total Congestion rent(\$/hr)	Priority location
1	7292.65	100-103
2	7654.62	49-51
3	7839.766	26-30
4	8074.32	103-105
5	8316.95	38-65
6	8331.603	45-49
7	8445.558	49-69
8	9616.89	47-69
9	10581.12	100-104
10	12062.01	80-96

Table 13: Priority Table based on Generation cost with TCSC for IEEE 118 bus system

Priority	Total Generation Cost(\$/hr)	Priority location
1	131697.6	26-30
2	131812.4	38-65
3	133336.6	100-103
4	133925	49-51
5	135275.1	103-105
6	136835.8	49-69
7	140123	45-49
8	148453.8	100-104
9	168027.9	80-96
10	169867.1	47-69



Table 14: Priority Table based on Congestion rent with TCPAR for IEEE 118 bus system

Priority	Total Congestion rent(\$/hr)	Priority location
1	7495.37	100-104
2	7597.412	38-65
3	7641.06	80-96
4	7737.552	45-49
5	7793.512	49-51
6	7797.928	103-105
7	7798.072	47-69
8	7798.457	49-69
9	7800.17	100-103
10	7816	26-30

Table 15: Priority Table based on Generation cost with TCPAR for IEEE 118 bus system

Priority	Total Generation Cost(\$/hr)	Priority location
1	131450.7	49-51
2	131458.3	103-105
3	131463.3	100-103
4	131489.6	45-49
5	131493.9	47-69
6	131494.3	49-69
7	131508.3	26-30
8	131547.5	38-65
9	131563.5	80-96
10	131663.5	100-104

For each line in the priority table based on LMP Difference, TCPAR is located in the line with a phase shift angle of 4.5° and total congestion rent and total generation cost is calculated and tabulated in the table 14,15. By observing table 14, the first best location for TCPAR to minimize total congestion rent is line 100-104. By observing table 15, the first location for TCPAR to minimize the total generation cost is line 49-51. By comparing the total congestion rent and total generation cost by placing TCSC and TCPAR, it is observed that the minimum generation cost with TCSC is 131697.6 (\$/hr) and minimum generation cost with TCPAR is 131450.7 (\$/hr). It is observed that the total generation cost can be reduced by placing of TCPAR than by placing of TCSC. By observing all the tables, the first 10 best locations for TCSC and TCPAR can be selected depending on the criteria of selection for congestion rent minimization and for generation cost minimization.

5. Conclusions

The Proposed method is for locating TCSC and TCPAR to manage congestion in deregulated power systems. The proposed method is based on LMPs that are by-product of OPF problem formulation. The proposed method is tested on an IEEE 24rts system, an IEEE 57 bus system, and an IEEE 118 bus system and is observed that depending on the criteria of requirement, we can capture the best location of TCSC and TCPAR. It is also observed from the results that by placing TCPAR, the minimum generation cost is reduced than by placing TCSC.

Nomenclature

$V_i \angle \delta_i$	Complex voltage at bus i
$V_j \angle \delta_j$	Complex voltage at bus j



P_{ij}	Real power flow from bus i to bus j
Q_{ij}	Reactive power flow from bus i to bus j
P_L	Real power losses in the line
Q_L	Reactive power losses in the line
P'_{ij}	Real power flow from bus i to bus j with TCSC
Q'_{ij}	Reactive power flow from bus i to bus j with TCSC
P_L	Real power losses in the line with TCSC
Q_L	Reactive power losses in the line with TCSC
P'_i	Real power injection at bus i
Q'_i	Reactive power injection at bus i
C_i	Generator cost of generator i
P_{G_i}	Real power generation at bus i
ρ_i	Spot price at bus i
λ_e	Marginal energy component of Locational marginal Price
$\lambda_{L,i}$	Marginal loss component of Locational marginal Price at bus i
$\lambda_{C,i}$	Marginal Congestion component of Locational marginal Price at bus i
TCC	Total Congestion rent

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Biographies



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Fuzzy PI Controller for BLDC motors Using Variable Sampling Effect

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Abstract

Variable sampling is important issue for the motor drives with low resolution position sensors. This paper proposes a variable sampling effect for Brushless DC motor (BLDC) drives using fuzzy PI (proportional and integral) controller using SIMULINK. The controller uses three fuzzy logics and three PI controllers to achieve variable sampling control. The simple structure of the fuzzy PI controller for BLDC motor considering variable sampling effect is not only implemented easily, but also robust in variable speed control system. The Simulink software was used to simulate the proposed scheme. The results are obtained for variable speed.

Keywords: variable sampling, discrete-time, SIMULINK, Fuzzy, PI control.

1.INTRODUCTION

Since 1980's new design concept of permanent magnet brushless motors has been developed. The Permanent magnet Brushless motors are categorized into two types based upon the back EMF waveform, brushless AC (BLAC) and brushless DC (BLDC) motors [2]. BLDC motor has trapezoidal back EMF and quasi-rectangular current waveform. BLDC motors are rapidly becoming popular in industries such as Appliances, HVAC industry, medical, electric traction, automotive, aircrafts, military equipment, hard disk drive, industrial automation equipment and instrumentation because of their high efficiency, high power factor, silent operation, compact, reliability and low maintenance [1]. To replace the function of commutators and brushes, the BLDC motor requires an inverter and a position sensor that detects rotor position for proper commutation of current. The rotation of the BLDC motor is based on the feedback of rotor position which is obtained from the hall sensors. BLDC motor usually uses three hall sensors for determining the commutation sequence. In BLDC motor the power losses are in the stator where heat can be easily transferred through the frame or cooling systems are used in large machines. BLDC motors have many advantages over DC motors and induction motors. Some of the advantages are

better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges [2]. Up to now, over 80% of the controllers are PI (Proportional and integral) controllers because they are facile and easy to understand [3]. The PI control method is a linear control method and do not work well in some discrete-time system. This is because controlled planes become nonlinear in variable sampling systems. Variable sampling systems describe a class of systems whose sensor outputs are obtainable only at some situations not specified by the sampling mechanism. The BLDC motor usually uses three or more Hall sensors to obtain rotor position and speed measurements. There are only a few sensors available to the motor. The measurement would be available only at discrete instances. Depending on the number of poles, there may be six or twelve sensor pulses per rotation. The sampling time thus becomes a variable according to the motor speed. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI controllers and have better noise rejection capabilities. The computer simulation plays very important roles in research and development of power electronic devices because of its high maneuverability, low cost and ability to speed up system implementation. The SIMULINK is a model operation programmer and the simulation model can be easily developed by addition of new sub-models to cater for various control functions. In this paper, we propose the fuzzy PI controller considering variable sampling effect for BLDC motor drive. It is not only easy to understand but also more robust. We use three fuzzy logics and three PI controllers at the same time. The paper is organized as follows: Section 2 explains about construction and operating principle of BLDC motor, Section 3, 4, 5 and 6 elaborates the fuzzy logic controller, continuous model, variable sampling trigger and discrete time speed variable time estimator of BLDC motor, Section 7 introduces the fuzzy BLDC motor system in



fixed sampling time, section 8 presents the fuzzy PI controller for BLDC motor considering variable sampling time. The simulation results are presented in detail in Section 9 and Section 10 concludes the paper.

2. Construction and Operating Principle of BLDC Motor

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the “slip” that is normally seen in induction motors. BLDC motor is constructed with a permanent magnet rotor and wire wound stator poles. Stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Figure 1. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.



Figure 1: Stator of a BLDC motor

Rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are used to make permanent magnets. Now a days, rare earth alloy magnets are gaining popularity.

Hall Sensors : The commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor as shown in figure 2. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. Each

commutation sequence has one of the windings energized to positive power the second winding is negative and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field [2].

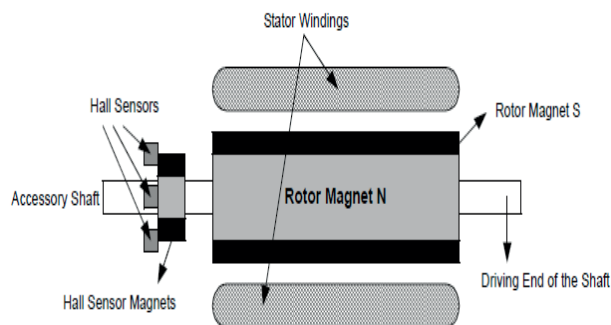


Figure 2: Rotor and Hall sensors of BLDC motor

Commutation Sequence : Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. It takes six steps to complete an electrical cycle. In Synchronous, with every 60 electrical degrees, the phase current switching should be updated as shown in figure 3. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles/rotations equals the rotor pole pairs. A 3-phase bridge inverter is used to control the BLDC motor. There are six switches and these switches should be switched based on the Hall sensor inputs. The Pulse width modulation techniques are used to switch ON or OFF the switches. To vary the speed, these signals should be Pulse Width Modulated (PWM) at a much higher frequency than the motor frequency. The PWM frequency should be at least 10 times that of the maximum frequency of the motor. When the duty cycle of PWM is varied within the sequences, the average voltage supplied to the stator reduces, thus reducing the speed. Another advantage of having PWM is that, if the DC bus voltage is much higher than the motor rated voltage, the motor can be controlled by limiting the percentage of PWM duty cycle corresponding to that of the motor rated voltage. This adds flexibility to the controller to hook up motors with different rated voltages and match the average voltage output by the controller, to the motor rated voltage, by controlling the PWM duty cycle. The speed and torque of the motor depend on the strength of the magnetic field generated by the energized windings of the motor, which depend on the current through them. Therefore adjusting the rotor voltage (and current) will change the motor speed.



Hall Sensor code	Phase	Active drive	
101	1	PWM1	PWM6
100	2	PWM1	PWM5
110	3	PWM3	PWM5
010	4	PWM3	PWM4
011	5	PWM2	PWM4
001	6	PWM2	PWM6

Figure 3: Commutation Sequence

3. FUZZY LOGIC CONTROL OF BLDC MOTOR

The Fuzzy Logic tool was introduced in 1965, also by Lotfi Zadeh and is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership the important concept of computing with words. It provides a technique to deal with imprecision and information granularity. The fuzzy theory provides a mechanism for representing linguistic constructs such as “many,” “low,” “medium,” “often,” “few”. In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. The traditional binary set theory describes crisp events, events that either do or do not occur. It uses probability theory to explain if an event will occur, measuring the chance with which a given event is expected to occur. The theory of fuzzy logic is based upon the notion of relative graded membership and so are the functions of mentation and cognitive processes.

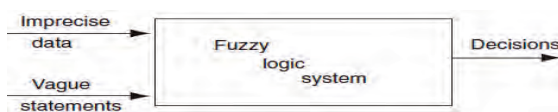


Figure : A fuzzy logic system

Fuzzification is an important concept in the fuzzy logic theory. Fuzzification is the process where the crisp quantities are converted to fuzzy (crisp to fuzzy). By identifying some of the uncertainties present in the crisp values, we form the fuzzy values. The conversion of fuzzy values is represented by the membership functions. In any practical applications, in industries, etc., measurement of voltage, current, temperature, etc., there might be a negligible error. This causes imprecision in the data. This imprecision can be represented by the membership functions. Hence Fuzzification is performed. Thus Fuzzification process may involve assigning membership values for the given crisp quantities. There are various methods to assign the membership values or the membership functions to fuzzy variables. The assignment can be just done by intuition or by using some algorithms or logical procedures. The methods for assigning the membership values are Intuition, Inference, Rank ordering, Angular fuzzy sets, Neural networks, Genetic algorithms, and Inductive seasoning. Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using Defuzzification process. The Defuzzification has the capability to reduce a fuzzy

to a crisp single-valued quantity or as a set, or converting to the form in which fuzzy quantity is present. Defuzzification can also be called as “rounding off” method. Defuzzification reduces the collection of membership function values in to a single scalar quantity. MATLAB software is used here for realizing the Fuzzy control of BLDC motor.. MATLAB has proven to be a very flexible and usable tool for solving problems in many areas. It is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. It is an interactive system whose basic elements are an array that does not require dimensioning. This allows solving many computing problems, especially those with matrix and vector formulations.

4. CONTINUOUS TIME MODEL OF BLDC MOTOR

The characteristic equations of BLDC motors can be rewritten as

$$\omega = (T_e - T_l) / (J s + D) \quad (1)$$

$$T_e = K_T \cdot i \quad (2)$$

$$i = (V - K_e \omega) / (L s + R) \quad (3)$$

where ω is motor speed, T_e is electromagnetic torque developed, T_l is load torque, K_T is torque constant, K_e is back-EMF constant, L is armature inductance, i is armature current, V is terminal voltage, and R is terminal resistance.

$$\frac{\omega}{V} = \frac{K_T}{(L s + R)(J s + D) + K_T K_e} \quad (4)$$

Influence from PWM scheme was also considered. The voltage command (V^*) is compared with triangle wave to create the gate signal. Then, the gate signal dot the voltage of DC bus (320V) to produce PWM waveform of inverter.

The detail block is shown in figure 4.

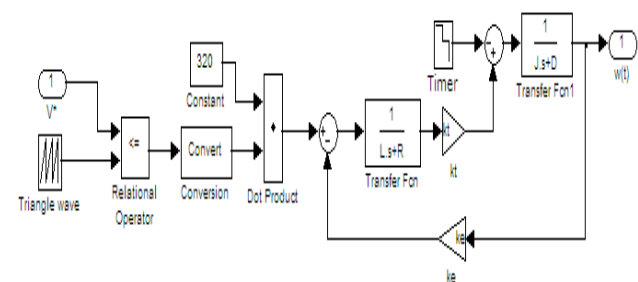


Figure 4: Continuous time model of BLDC motor

Variable sampling trigger: The sampling time is variable according to BLDC motor speed and the 4 poles of BLDC consists of 12 Hall feedback signals per mechanical revolution, means there is a hall sensor per $2\pi/12$ radian. There must be a sample trigger, when the BLDC motor passed through $2\pi/12$ radians [3]. To simulate the variable sampling phenomenon, we integrate rotor speed to angle, and divide angle by $\pi/6$. When the



angle of BLDC motors is divisible by $\pi/6$, the trig should be produced for the discrete time speed and variable sampling time constant estimator. Unfortunately, the remainder may be equal to zero in SIMULINK, because the continuous simulation is based on the equivalent of very fast discrete time system. So, we use the boundary to catch the moment which the angle of BLDC motors is divisible by $\pi/6$. The block diagram is as shown in figure 5.

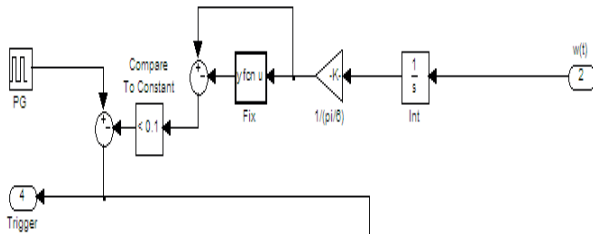


Figure 5: Variable sampling trigger

Discrete Time Speed And Variable Sampling Time Constant Estimator: The sampling trigger trigs the sample and hold block to sample speed, then the variable sampling time interval can be calculated by sampled time speed. The unit of speed is rpm and the included angles between every hall sensors are $2\pi/12$. In order to avoid dividing by zero, the initial speed is set to 1rpm and initial time constant to the sample time in the lowest controllable speed. The block diagram is shown in figure 6.

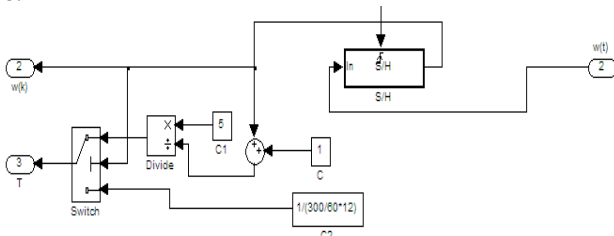


Figure 6: Variable Speed and Sampling time estimator

BLDC Motor System In Fixed Sampling Rate: In a basic digital control system, the sampling time is taken to be fixed. The discrete-time control rule base on the fixed sampling rate is not robust in variable speed control, especially in low resolution position feedback. For instance, the discrete-time proportional, integral (PI) control is shown as follows, The proportional control,

$$u(k) = K_p \cdot e(k) \quad (5)$$

The integral control,

$$u(k) = u(k-1) + K_i \cdot e(k) \quad (6)$$

where K_p is the proportional gain and K_i is the integral gain. Three different PI controllers are employed in this paper and fuzzy logic controllers are used to scale speed error for the three PI controllers to achieve robust variable speed control. The block diagram of PI controller is shown below.

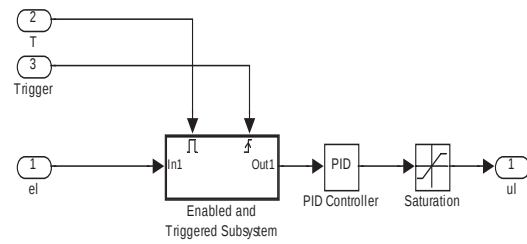


Figure 7: PI controller for BLDC motor

Fuzzy Pi Controller For BLDC Motor Using Variable Sampling Time:

In 1990's, fuzzy logic techniques have gained much interest in the application of control system. They have a real time basis as a human type operator, which makes decision on its own basis. But the complexity of the fuzzy logic controller is the main problem about designing fuzzy logic controllers. The complexity is that the size of the fuzzy rule base of the fuzzy controller increases as the number of fuzzy if-then rules increases and the number of rules increases exponentially as the number of input variables of the fuzzy controller increases. In order to reduce the complexity, we present the fuzzy PI controller for BLDC motors considering variable sampling effect. The block diagram is presented in figure 8.

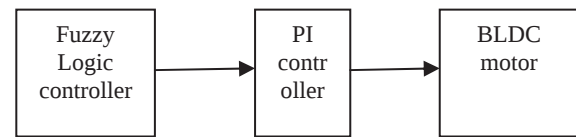


Figure 8: Block diagram of Fuzzy PI controller using variable sampling time

The PI controller that we present includes three dual inputs but single rule for the fuzzy logic and three PI controllers in different sampling time, as shown in figure 9. Although there are two inputs (speed error and rotor speed) in fuzzy logic, the fuzzification, control rule and defuzzification are based on the rotor speed (ω). The major work of the fuzzy logic is scaling speed error for PI controller.

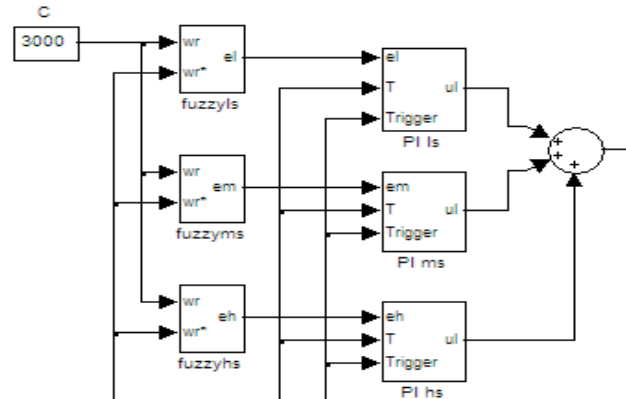


Figure 9: Fuzzy PI controller for BLDC motor using variable sampling time

Three fuzzy logics are based on rotor speed (ω) and the speed is between 0 to 3000 rpm. The input membership functions of the fuzzy sets are trapezoidal and triangular



exception. Figure 5 shows the membership distribution where the fuzzy variables are labeled with 'LS', 'MS' and 'HS' to represent low speed, median speed and high speed. The mathematics of the membership functions are shown below.

$$y_L(\omega) = \begin{cases} 1 & \text{for } \omega < 500 \\ \frac{1500 - \omega}{1000} & \text{for } 500 \leq \omega \leq 1500 \\ 0 & \text{for } \omega > 1500 \end{cases} \quad (7)$$

$$y_M(\omega) = \begin{cases} 0 & \text{for } \omega < 500 \\ \frac{\omega - 1500}{1000} & \text{for } 500 \leq \omega \leq 1500 \\ \frac{2500 - \omega}{1000} & \text{for } 1500 \leq \omega \leq 2500 \\ 0 & \text{for } \omega > 2500 \end{cases} \quad (8)$$

$$y_H(\omega) = \begin{cases} 1 & \text{for } \omega < 1500 \\ \frac{\omega - 1500}{1000} & \text{for } 1500 \leq \omega \leq 2500 \\ 0 & \text{for } \omega > 2500 \end{cases} \quad (9)$$

y_L is the membership degree of the fuzzy logic in low speed and y_M is the membership degree of the fuzzy logic in median speed and y_H is the membership degree of the fuzzy logic in high speed (ω) is the rotor speed as shown below.

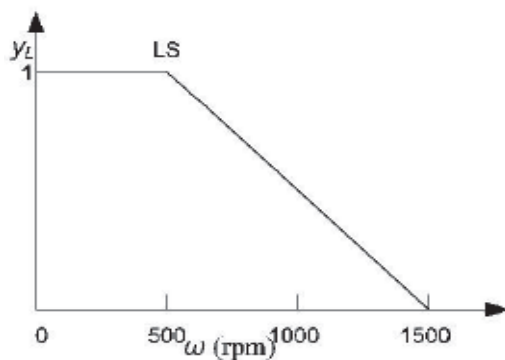


Figure 10: The input membership of fuzzy logic in low speed

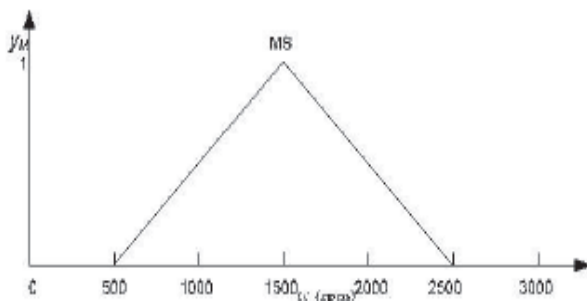


Figure 11: The input membership of fuzzy logic in median speed

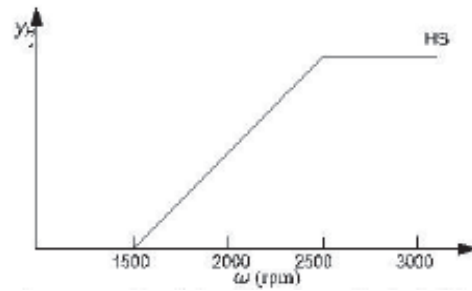


Figure 12: The input membership of fuzzy logic in high speed

Fuzzy control rule

The if-then rules of the fuzzy logic can be expressed as,

$$R_L: \text{If } \omega \text{ is LS, then } e_L \text{ is } e \quad (10)$$

$$R_M: \text{If } \omega \text{ is MS, then } e_M \text{ is } e \quad (11)$$

$$R_H: \text{If } \omega \text{ is HS, then } e_H \text{ is } e \quad (12)$$

R_L , R_M , and R_H are the control rules in different speed. e_L , e_M , and e_H are the outputs of fuzzy logic. e is the speed error. There are only three control rules.

Defuzzification

To calculate the output, a multiplication is used for defuzzification.

$$e_L = e \cdot y_L \quad (13)$$

$$e_M = e \cdot y_M \quad (14)$$

$$e_H = e \cdot y_H \quad (15)$$

From the scaled speed error, the three PI controllers can calculate three voltage commands. As the scaled speed error is based on rotor speed, the fuzzy PI controllers can achieve variable sampling in BLDC motor drives using Hall sensor. The block diagram of fuzzy logic controller is shown in figure 13 and the block diagram of the whole system is shown in figure 14.

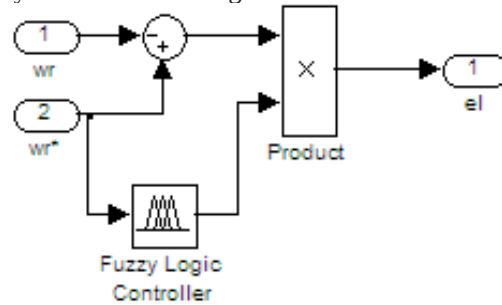


Figure 13: Fuzzy logic controller for BLDC motor

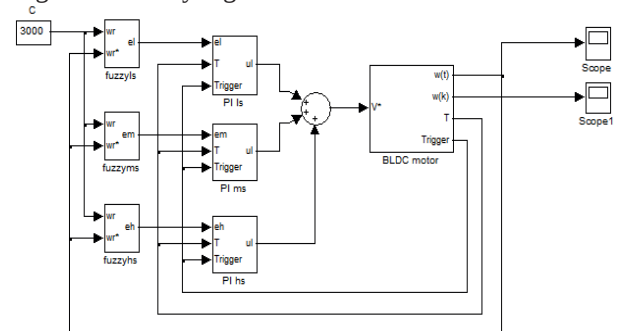


Figure 14: Fuzzy PI controller for BLDC motor



5. RESULTS AND CONCLUSION

The simulation result includes the speed responses of the variable sampling PI controller, which is designed for high speed situation and the fuzzy PI controllers based on variable sampling effect. The variable of the speed command is from 500 rpm to 1500 rpm and then to 3000 rpm. The waveforms of the variable speeds considering variable sampling effect are shown below.

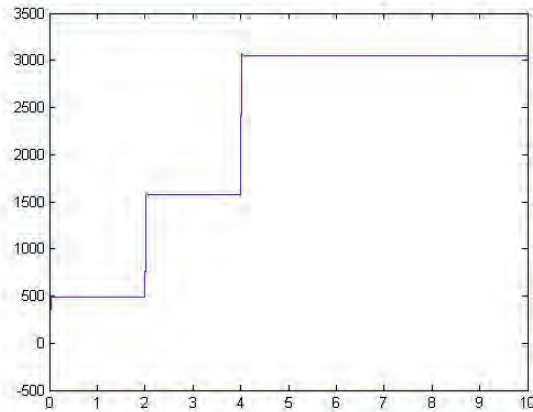


Figure 15: Fuzzy PI controller for BLDC motor considering variable sampling effect $w(t)$

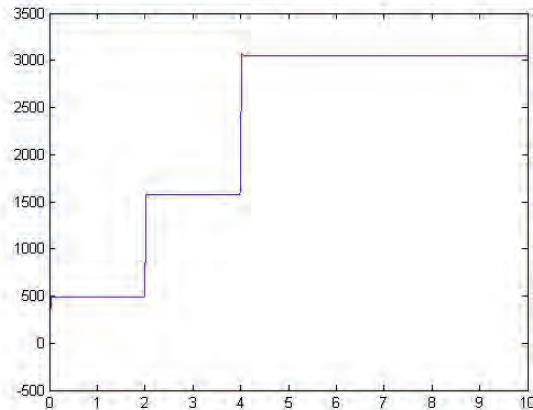


Figure 16: Fuzzy PI controller for BLDC motor considering variable sampling effect $w(k)$

The BLDC motor parameters are described in Table I.

Specifications	Units
No. of poles	4
Moment of inertia, J	0.0002 Kg-m ²
Damping constant, D	0.000001
Stator resistance, R	5.17
Stator Inductance, L	24mH
Back-EMF constant, k_e	0.28383 V-s/rad
Torque constant, k_t	0.28383 V-s/rad
Terminal Voltage, V	320V

Table I: Motor parameters

In this paper, fuzzy PI controller for BLDC motor considering variable sampling time was proposed. Three fuzzy logic controllers to scale speed error for the three PI controllers were used in this paper. Three subsystems for various sampling simulation have been presented. First is the continuous time model of BLDC motor, the

second is the variable sampling time and the third is the discrete time speed and variable sampling time constant estimator. The results have been presented and analyzed for different speed conditions.

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Use of Gain Scheduling Fuzzy Controller and Fuzzy Observer to Stabilize and Reject Disturbance in Nonlinear Magnetic Bearing Systems

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Abstract

In this paper, an Adaptive Neuro Fuzzy Inference System (ANFIS) used to design a gain scheduling fuzzy controller, and fuzzy reduced order observer based on gain scheduling method. The nonlinear model of a magnetic bearing system with imbalance complicated, and the coupling between various states cannot neglect. First, the proposed fuzzy control system constructed for decentralized linear systems at a wide range of operating points of air gap and current for different values of rotational speed. Second, the data collected used as training data for ANFIS to construct if-then rules and membership function. Results show that the proposed fuzzy control system achieved stability and can eliminate disturbances at any rotational speed.

Keyword: ANFIS, Fuzzy gain scheduling, Magnetic bearing, Neuro-Fuzzy Reduced order observer.

1. Introduction

Magnetic bearings used in industrial and manufacturing applications due to their unique properties, such as that high speed of rotation, operate in environments not amenable to the use of lubrication, and non-contacting nature leading to an elimination of frictional losses. Magnetic bearing systems are unstable and fast. Therefore, they need well designed controllers to keep it in precision position and to eliminate unbalance vibrations at any rotational speed. Rotor unbalances usually generated disturbance forces and moments. Disturbance forces are due to the eccentricity between the center of rigid body and the center of the shaft (static unbalance), but disturbance moments are due to the inclination angle between the axis of symmetry of rigid body and rotation axis (dynamic unbalance).

Several methods used for reducing or eliminating the effect of unbalance for example: compensating unbalance force by generating electromagnetic force to cancel it [1-3], a notch filter for achieving automatic balancing [4,5] and Q- parameterization theory, which used to stabilize the rotor position and evaluate noise rejection and robustness to parametric uncertainty[6-9]. Also, this problem solved by using gain scheduled robust

controller based on the Loop Shaping Design Procedure (LSDP) [10]. A recursive and a non-recursive control law with simultaneous estimation, and a recursive control law with gain scheduling according to operating speed presented by [11], automatic learning control proposed by [12] and a full order sliding mode controller presented by [13]. An adaptive disturbance rejection control technique introduced by [14]. Kang and Lyuu [15] proposed a design technique for a disturbance feed forward compensation control to attenuate disturbance responses. [16] presented a saturated force controller targeted for magnetic levitation systems that asymptotically regulates the position of a target mass in the presence of a nonlinear, bounded, periodic disturbance. Finally, the working principle of active disturbance rejection controller (ADRC) introduced by [17].

In this paper, a combination of ANFIS and gain scheduling techniques proposed to derive fuzzy membership functions and fuzzy if-then rules for gain scheduling fuzzy controller and fuzzy reduced order observer to cancel disturbances at any rotational speed and achieved nonlinear system stability.

The remainder of the paper organized as follows: Section (2) derived the mathematical model. Section (3) emphasized on problem statement. Section (4) mentioned the results and conclusion in Section (5).

2. Mathematical model

2.1 Equations of Motion

Consider the vertical shaft magnetic bearing system shown in Figure 1. The fundamental equations of motion for the rotor [18] in four radial degrees of freedom are:

$$\begin{aligned} m\ddot{x} + me\omega^2 \sin\omega t &= f_{ax} + f_{bx} \\ m\ddot{y} + me\omega^2 \cos\omega t &= f_{ay} + f_{by} \end{aligned} \quad (1)$$

$$I_x\ddot{\theta} - I_z\omega\dot{\theta} - \varepsilon\omega^2(I_x - I_z)\sin\omega t = af_{ax} - bf_{bx}$$

$$I_x\ddot{\theta} + I_z\omega\dot{\theta} + \varepsilon\omega^2(I_x - I_z)\cos\omega t = -af_{ay} + bf_{by}$$



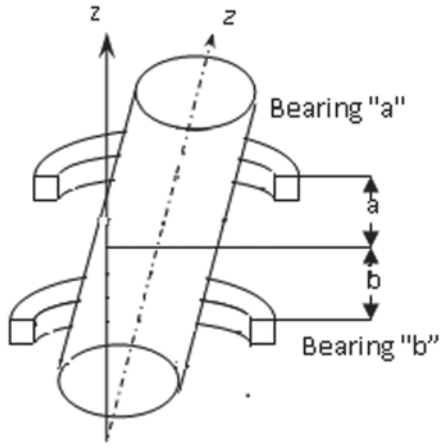


Figure1. Rigid rotor with two radial bearings

where

a, b :Distances from center to bearings a & b .

e :Eccentricity μm .

I_i : Moment of inertia around i axis $kg.m^2$.

m : Rotor mass kg .

f_{ij} : Forces in x & y axis at bearings a & b .

2.2 Electromagnet Equations

Forces $f_B = (f_{ax}, f_{bx}, f_{ay}, f_{by})$ can be expressed in terms of coil current i and the gap length S as follows:

$$f_B = K \left(\frac{i_B^2}{S_B^2} \right), \quad K = \frac{\mu_0 A_g N^2}{4} \quad (2)$$

Where

A : Area of magnetic coil mm^2 .

i_B : coil current of j^{th} stator electromagnet *Amper*.

N : Number of turns in each electromagnet coils.

S : Steady state air gap length mm .

Linearize forces as a function of a current and air gap.

$$f_B = K_{SB} Z_B + K_{IB} i_B$$

where

$$i_B = (i_{ax} \quad i_{bx} \quad i_{ay} \quad i_{by}) \quad (3)$$

$$K_{SB} = 2 \text{diag} .(k_{sa}, k_{sb}, k_{sa}, k_{sb})$$

$$K_{IB} = 2 \text{diag} .(k_{ia}, k_{ib}, k_{ia}, k_{ib})$$

The voltage across the j electromagnet coils can express as follows:

$$u_j = R i_j + L \frac{d i_j}{dt} + k_i \dot{z}_B(j) \quad (4)$$

where

R : electromagnetic coil resistance *ohm*.

L : coil inductance *H*.

$$z_B = [x_a \quad x_b \quad y_a \quad y_b]^T$$

Let equations (1-4) be written in the form

$$M \ddot{Z} = G \dot{Z} + f + E w(t) \quad (5)$$

where

$$M = \text{diag}(m, I_x, m, I_x)$$

G =zero matrix excepted $g_{24} = -g_{42} = \omega I_z$

$$E = \omega^2 \begin{bmatrix} me & 0 \\ \varepsilon(I_x - I_z) & 0 \\ 0 & me \\ 0 & \varepsilon(I_x - I_z) \end{bmatrix}, w(t) = \begin{bmatrix} \sin \omega t \\ \cos \omega t \end{bmatrix} \quad (6)$$

Transform equation (5) to bearing coordinates

$$M_B \ddot{z}_B = G_B \dot{z}_B + f_B + E_B w(t)$$

$$M_B = T_B^T M T_B \quad (7)$$

$$G_B = T_B^T G T_B$$

$$E_B = T_B^T E$$

T_B is the transformation matrix from principle axes to bearing axes.

If we assume that the force displacement factor and force current factor are the same for bearings (a) and (b), then:

$$\ddot{z}_B = M_B^{-1} G_B \dot{z}_B + M_B^{-1} K_{SB} z_B + M_B^{-1} K_{IB} i_B + M_B^{-1} E_B w(t) \quad (8)$$

The state vector composed of displacements, their derivatives and electrical currents in coils. For this model, the voltage is the input variable. The final state space model is:

$$\dot{x}_B = A_B x_B(t) + B_B u(t) + \Gamma_1 w(t) \quad (9)$$

$$y = C x_B(t)$$

$$x_B = \begin{bmatrix} z_B \\ \dot{z}_B \\ i_B \end{bmatrix}$$

$$A_B = \begin{bmatrix} 0_{4 \times 4} & I_{4 \times 4} & 0_{4 \times 4} \\ (M_B^{-1} K_{SB})_{4 \times 4} & (M_B^{-1} G_B)_{4 \times 4} & (M_B^{-1} K_{IB})_{4 \times 4} \\ 0_{4 \times 4} & (-\frac{K_i}{L})_{4 \times 4} & (-\frac{R}{L})_{4 \times 4} \end{bmatrix}$$

$$B_B = \begin{bmatrix} 0_{4 \times 4} \\ 0_{4 \times 4} \\ (1/L)_{4 \times 4} \end{bmatrix}$$

$$C = [I_{4 \times 4} \quad 0_{4 \times 4} \quad 0_{4 \times 4}]$$

$$\Gamma_1 = \begin{bmatrix} 0_{4 \times 2} \\ (M_B^{-1} E_B)_{4 \times 2} \\ 0_{4 \times 2} \end{bmatrix}$$

Assume that, the rotational speed equal zero and there is no disturbance. Then, we can divide the Multi-Input-Multi-Output (MIMO) system to four Single-Input-Single-Output (SISO) separate subsystems using decentralized method [19]. Discretization each subsystem individually by using a zero-order hold at a sampling time of 0.001 (sec). The following SISO discrete time systems are:

$$z(k+1) = \phi z(k) + \Gamma u(k) \quad (10)$$

$$Y(k) = C z(k)$$

Disturbance forces in whole system obey the following equations [20]:



$$\begin{aligned}\dot{x}_d &= F_d x_d \\ w &= H_d x_d \\ \text{where}\end{aligned}\quad (11)$$

$$F_d = \omega^2 \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \quad H_d = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The discrete model is done by zero order hold with sampling time t_s sec, as

$$\begin{aligned}x_d(k+1) &= \phi_d x_d(k) \\ w(k) &= H_d x_d(k)\end{aligned}\quad (12)$$

We augmented the system model with disturbance model, so that the state space equations become

$$\begin{aligned}\begin{bmatrix} x_B(k+1) \\ x_d(k+1) \end{bmatrix} &= \underbrace{\begin{bmatrix} \phi & \Gamma_d \\ 0 & \phi_d \end{bmatrix}}_{\phi_w} \begin{bmatrix} x_B(k) \\ x_d(k) \end{bmatrix} + \underbrace{\begin{bmatrix} \Gamma \\ 0 \end{bmatrix}}_{\Gamma_w} u(k) \\ Y(k) &= \underbrace{\begin{bmatrix} C & 0 \\ C_w & C_d \end{bmatrix}}_{C_w} \begin{bmatrix} x_B(k) \\ x_d(k) \end{bmatrix}\end{aligned}\quad (13)$$

where

$$\Gamma_d = \begin{bmatrix} 0 \\ M_B^{-1} E_B H_d \\ 0 \end{bmatrix}, \quad x_d(k) = \begin{bmatrix} \sin \omega t \\ \cos \omega t \end{bmatrix} \quad \& \quad \phi = e^{-A_B t_s}$$

3. Problem statement

The objective of design strategies is to stabilize the magnetic bearing system and eliminate the disturbance. To facilitate the control development, we design a gain scheduling fuzzy controller and construct a fuzzy reduced order observer based on gain scheduling.

Fuzzy controller contains a fuzzification, fuzzy inference, and defuzzification. Fuzzification convert a crisp set of input data to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms and membership functions. Fuzzy inference combines the facts obtained from the fuzzification with the fuzzy rule base and conducts the fuzzy reasoning process. In the defuzzification the resulting fuzzy output is mapped to a crisp output using the membership functions. The design approach described as follows:

(1) Define the domain of interest and set operating points. These points distributed uniformly through the scheduling variable domain.

(2) For each operating point, find the linearize model of the plant and determine the feedback and reduced order observer gains. This achieved by using pole placement method.

(3) Design a fuzzy gain scheduling controller and fuzzy reduced order observer based on gain scheduling using ANFIS technique. The scheduling variables are the rotational speed, steady state air gap and steady state current, while outputs are the control action and estimator gain.

(4) Combination the nonlinear plant with both gain scheduling fuzzy controller and Fuzzy reduced order observer as shown in Figure 2.

3.1 Controller design

The proposed controller used pole placement method to determine the feedback gain K , which satisfies the control law:

$$u = -Kz \quad (14)$$

The feedback gains obtained via decentralized controller for each subsystem; assume that the rotational speed is zero. Then collect and rearrange the obtained feedback gains to the form given in the gain matrix for the complete system.

$$\begin{bmatrix} K_{xa} & 0 & 0 & 0 \\ 0 & K_{xb} & 0 & 0 \\ 0 & 0 & K_{ya} & 0 \\ 0 & 0 & 0 & K_{yb} \end{bmatrix}_{12 \times 12}$$

where $K_{xa}, K_{xb}, K_{ya}, K_{yb}$ are controllers of the subsystems respectively.

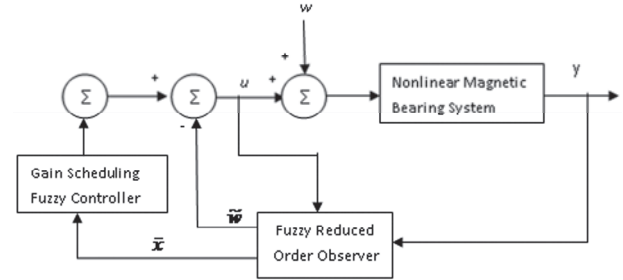


Figure 2. Block diagram for controlled magnetic bearing system

3.2 Gain scheduling fuzzy controller

The interest of Neuro-Fuzzy system has grown tremendously over the last few years. Fuzzy system designed to work with knowledge in the form of linguistic rules. However, the translation of these linguistic rules into the framework of fuzzy set theory depends on the choice of certain parameters, for which no formal method known. The optimization of these parameters can carry out by a neural network, which designed to learn from training data [21], [22]. Gain scheduling is a linear parameter varying feedback regulator whose parameters changed as a function of operating conditions. Then, we use linear behavior controllers for control nonlinear system. Fuzzy gain scheduling proposed to design high performance nonlinear controller. The feedback gains adjusted (scheduling) via member ship functions (MFs) in fuzzy if-then rules.

When desired gains at various operating points are available, we can apply the Neuro-Fuzzy technique (ANFIS) to construct and optimize the shape of MFs that can interpolate the gains with respect to several operating points. The gain scheduling fuzzy controller is show in Figure 3. Inputs to the premise part are the operating points of the air gap and current. While, inputs to consequent part are the state variable ($x, \dot{x}$ and i).



The gain scheduling fuzzy controller has the following if-then rules:

if x_0 is A_1 and i_0 is B_1 then $f_1 = k_{11}x + k_{12}\dot{x} + k_{13}i$.

if x_0 is A_2 and i_0 is B_2 then $f_2 = k_{21}x + k_{22}\dot{x} + k_{23}i$.

The gain vector k_i on the operating point (x_o, i_o) is expressed explicitly as

$$k_i = \frac{\mu_{A1}(x_o)\mu_{B1}(i_o)q_{1i} + \mu_{A2}(x_o)\mu_{B2}(i_o)q_{2i}}{\mu_{A1}(x_o)\mu_{B1}(i_o) + \mu_{A2}(x_o)\mu_{B2}(i_o)}$$

Where f_1 and f_2 are control actions at the certain operating point and μ_{Ai}, μ_{Bi} are membership grades of a linguistic label. In this controller, the feedback gains blended smoothly via MFs, then give linguistic meaning to the scheduling variables.

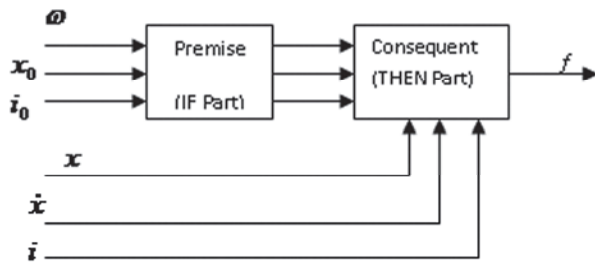


Figure 3. Gain scheduling fuzzy controller.

3.3. Neuro-fuzzy reduced order observer

When we design a feedback control system the rotational speed is ignored, but the stability of the closed loop is decreased when increase the rotational speed. Rotational speed causes disturbances, then to achieve more stability to the system disturbance rejection must be considered.

The disturbance rejection method depends on estimation of disturbance signal by the reduced order observer for linear system [23], then use it in the control law to force the error to be zero.

One of the main objectives of this paper is to design a neuro-fuzzy reduced order observer to reject disturbances in a nonlinear magnetic bearing system using ANFIS technique.

3.3.2 Design Approach

Design procedures described as follows: (1) Select the domain of interest in a magnetic bearing system, the rotational speed are between $2\pi 10$ to $2\pi 250$ rad/sec, the air gap are between ± 0.5 mm and the current are between ± 0.4 Ampere. (2) Design the reduced order observer for each subsystem and estimated observer gains for each operating point with different rotational speed. (3) Collect the estimator gains and the disturbances for the whole system. (4) Use the data obtained from the previous step as a training data for ANFIS to get MFs and IF-THEN rules.

A Neuro-Fuzzy observer has the following fuzzy if-then rules:

if u is A_1 and y is B_1 then $k_{11} = D_1$ and $k_{1j} = T_1$

if u is A_2 and y is B_2 then $k_{21} = D_2$ and $k_{2j} = T_2$

4. Results

Parameter values of magnetic bearing system show in Table I. The performance of a nonlinear magnetic bearing system examined. A MATLAB program using numerical Rung-Kutta fourth order method created. The motion in a z-direction is necessary to describe the rotor motion for the nonlinear model, so we designed a controller similar to one of the radial directions and joint it with the controller in the gain matrix. Note that there is no disturbance in a z-direction, then no need to design an estimator. Figures (4-6) show comparison between neuro-fuzzy controlled and uncontrolled nonlinear magnetic bearing system. The displacement and rotational about x and y axis and the displacement of z-axis of the rotor established with various operational speed $2\pi 40, 2\pi 100, 2\pi 200$ rad. We observe that the proposed neuro-fuzzy control system can eliminate the sinusoidal disturbance and achieve stability faster than uncontrolled nonlinear magnetic bearing (see Table II).

Table I. parameter values for magnetic bearing

Parameter	symbol	Value
Mass of rotor	m	14.46 kg
Mass moment of inertia in axial direction	I_z	0.0136 kg.m ²
Mass moment of inertia in radial direction	I_x	0.333 kg.m ²
Center distance to bearing (a)	a	0.13 m
Center distance to bearing (b)	b	0.13 m
Steady state current	i_o	0.38 Ampere
Steady state air gap	S_o	0.55 mm
Resistance of coil	R	10.7 ohm
Number of turns per coil	N	400 turns
Area of magnetic coil	A	1531 mm ²
Static unbalance	e	0.1 mm
Dynamic unbalance	ε	0.0004 rad

Table II Comparison between controlled and uncontrolled MB system

Settling Time (sec)		
Rotational speed	N-F controller	uncontrolled
$2\pi 40$ rad	0.05	1.2
$2\pi 100$ rad	0.02	1.2
$2\pi 200$ rad	0.025	1.2



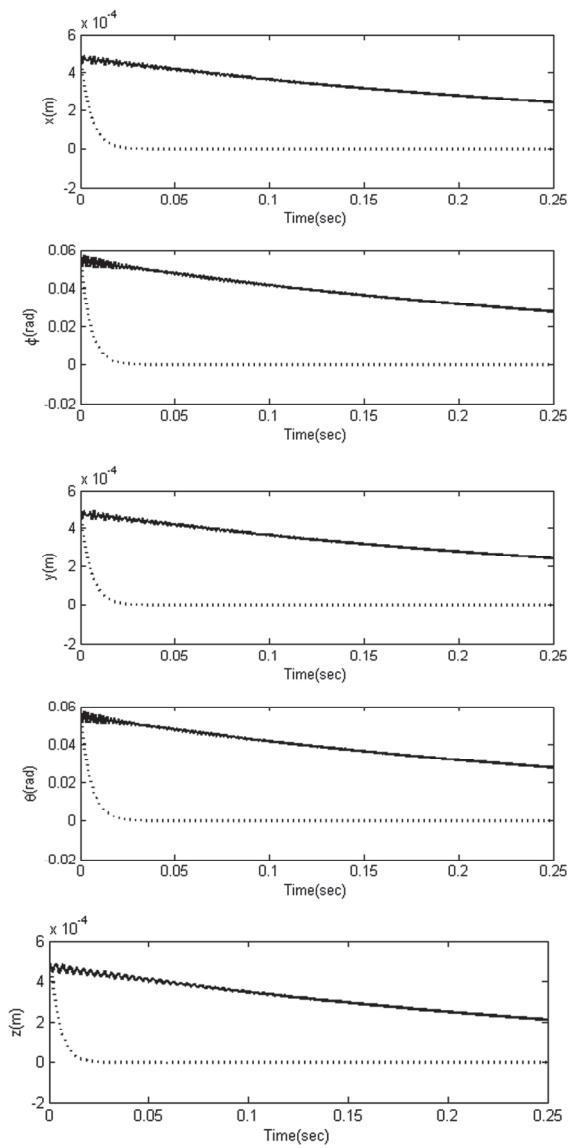


Figure 4. Response due to initial condition for $\omega = 2\pi 40$ rad/sec

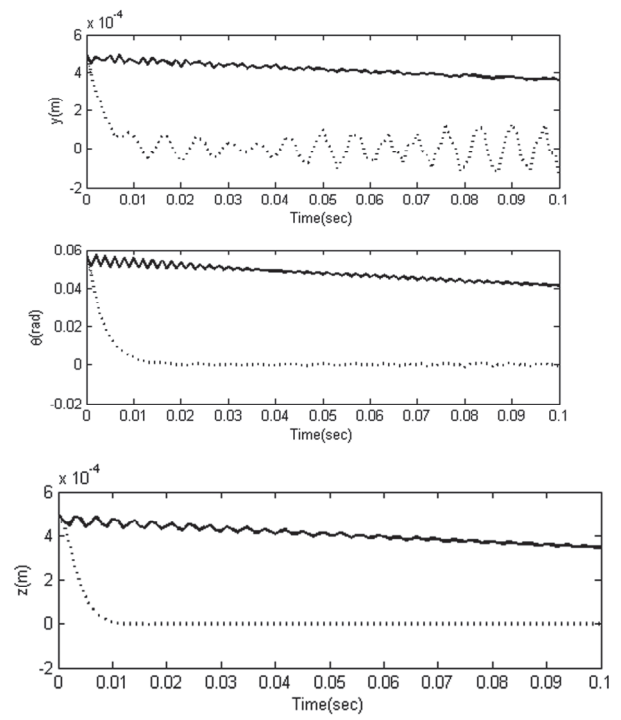
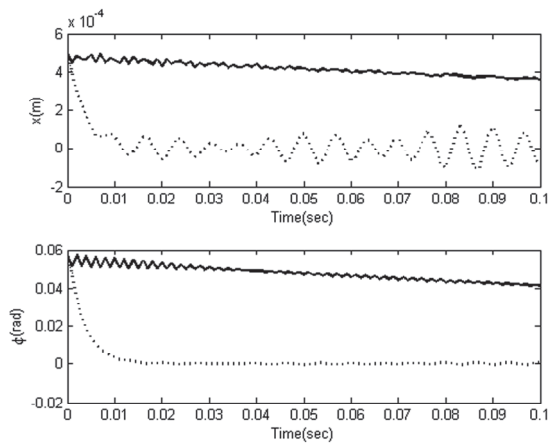
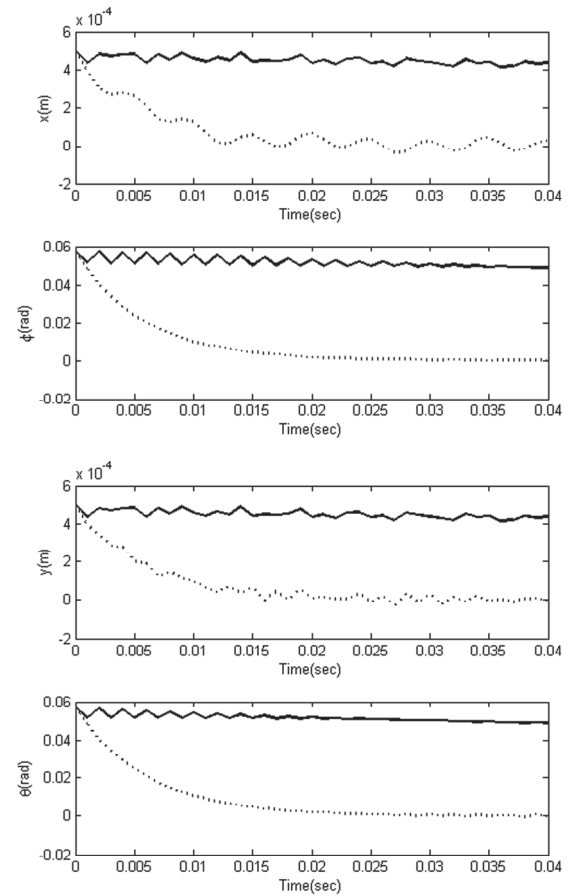


Figure 5. Response due to initial condition for $\omega = 2\pi 100$ rad/sec



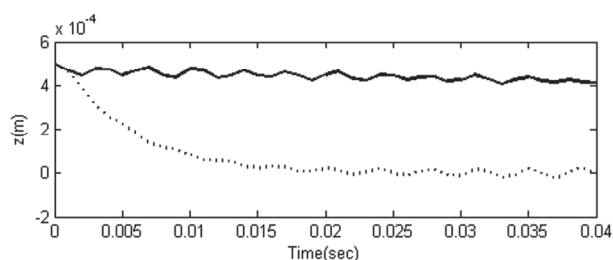


Figure 6. Response due to initial condition for $\omega = 2\pi 200$ rad/sec

5. Conclusion

In this paper, a gain scheduling fuzzy controller and a neuro-fuzzy reduced order observer designed to eliminate disturbances in a nonlinear magnetic bearing system for all operating speeds. A controller designed to stabilize the system and a fuzzy observer to estimate the disturbance and negative feed it back to cancel the actual one. A conventional controller and reduced order observer designed for several operating points with twenty five values of rotational speed. Then, obtain the controller and the observer gains and estimate disturbance to collect the training data. ANFIS technique used training data to determine membership functions and if-then rules for fuzzy controller and observer. The fuzzy observer combined with both fuzzy controller and nonlinear magnetic bearing system. Results show that, we can achieve stability and reject the disturbance at any rotational speed.

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Biography



Manar Eltantawie was born in Mansoura 1966, receive Bachelor degree in mechanical Design and production Engineering, Mansoura University, Egypt, in 1988, the Master degree in mechanical Design and production Engineering, Cairo University, Egypt, in 1995, and the PhD degree in Automatic Control,

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Speed Performance of Direct Torque Control for Three Level Inverter Fed Induction Motor: Sliding Mode Control Approach

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Abstract

In recent years, the research has been focused to find out different solutions for the induction motor control having the features of precise and quick torque response and reduction of the complexity of field oriented algorithms. The direct torque control (DTC) technique has been recognized as the viable solution to achieve these requirements. The direct torque control of induction motors fed by two level inverter has certain drawbacks like more torque, flux and current ripples in steady state, which results in incorrect speed estimations. This paper presented the direct torque control of induction motor fed by a three level neutral point clamped inverter used in high power applications. To improve the speed performance of the drive against uncertainties caused by load disturbances, an integral switching surface sliding mode speed controller (SMC) is proposed. To validate the proposed method, simulation results are presented.

Keywords: Direct torque control, Sliding mode control, Neutral point clamped inverter, space vectors.

Nomenclature

R_s, R_r	stator and rotor resistances
L_s, L_r, L_m	self and mutual inductances
P	number of poles
V_s	stator voltage
ψ_s, ψ_r	stator and rotor flux linkages
T_e	electromagnetic torque
B	friction coefficient
J	inertia constant
T_L	load torque.
ω_m	rotor mechanical speed

1. Introduction

The Induction Motor, of its well known advantages like simple construction, reliability, ruggedness, and low cost, has found wide spread industrial applications. IM control methods can be divided into scalar and vector control. In scalar control, which is based on relationships valid in steady state, only magnitude and frequency of voltage, current, and flux linkage space vectors are controlled.

Thus, the scalar control does not act on space vector position during transients. In vector control, magnitude, frequency and the instantaneous positions of voltage, current, and flux space vectors are controlled. Therefore, the vector control works on the positions of the space vectors and provides their correct orientation both in the steady state and during transients. In the vector control the motor equations are transformed in a coordinate system that rotates in synchronism with the rotor flux vector. The torque and flux components are identified and controlled independently to achieve a good dynamic response. There is a necessity of transforming the variables in the synchronously rotating reference frame to the stator reference frame to control actual currents/ voltages.

Direct torque control (DTC) method has become one of the high performance control strategies for induction motor to provide a very fast torque and flux control [1]. It is the direct control of torque and flux of an electrical motor by the selection through a look-up table, of the power converter voltage space vectors [2]. The advantages of DTC is its simple structure, no coordinate transformations, no current controllers are needed. Moreover the controller does not depend on motor parameters. DTC is considered to be a simple and robust control scheme which achieves quick and precise torque control response. DTC of induction motor is preferred because, this technique is based on the space vector approach, where the torque and flux of an induction motor can be directly and independently controlled without any coordinate transformation [3].

Three level inverters have become widespread in industrial applications since they were first proposed by Nabae in 1981 [4]. In comparison with a two level inverter, three level inverters perform in a better way in terms of reduction in the total harmonic distortion (THD) [5]. In a two level inverter DTC control strategy, the entire vector space is divided into six sectors. In this method torque and flux ripples are generated [6], [7]. Industrial applications exhibit significant uncertainties, so the performance of the system may deteriorate, if conventional controller such as PI controller is used. Because of this reasons it is worth to develop controllers



that have capabilities of handling uncertainties caused by parameter variations. The sliding mode control can offer good performance against insensitivities to load disturbance [8]. Hence, to improve the speed performance under uncertainties, a sliding mode speed controller (SMC) is used for FOC in [9].

The main objective of this paper is to develop an integral switching surface sliding mode speed controller to improve the speed performance, under uncertainties which is caused by load variations. The developed SMC is employed in the DTC of induction motor fed by neutral point clamped three level inverter. The speed performance of the system is tested for different load torques disturbances. Finally speed behavior of the system with and without SMC is observed and the results are generated.

The paper is organized as follows: Operation of neutral point clamped inverter is presented in section 2. The principle of direct torque control is presented in section 3. Section 4 presents the modulation strategy of three level DTC of induction motor. Integral sliding mode speed controller for DTC of induction motor is presented in section 5. Simulation results are presented in section 6 to illustrate the performance of the proposed method. Conclusions are presented in section 7.

2. Neutral Point Clamped Inverter

The three level neutral point clamped inverter has many advantages over the conventional two level inverter, such as smoother waveform, less distortion, less switching frequency and low cost [1]. The topology of a three level NPC inverter is shown in figure 1.

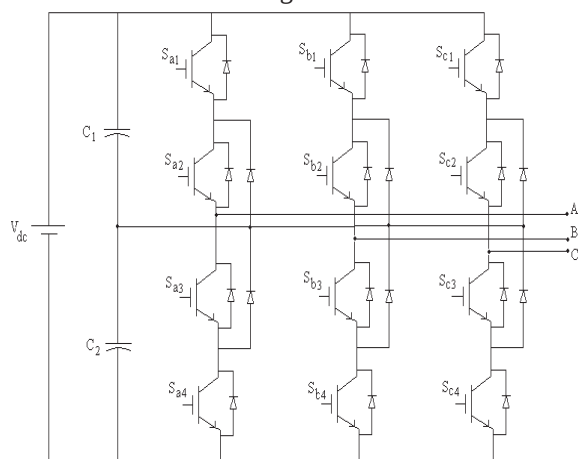


Figure 1. Schematic diagram of NPC three level Inverter

The three level inverter has a total of 27 switching states (3^3). When the upper switches S_{a1} , S_{a2} are in the on state, that corresponds to the state '1'. When the lower switches S_{a3} , S_{a4} are on, that corresponds to state '-1'. When the auxiliary switches S_{a2} , S_{a3} are on, that results in state '0'. The space vector diagram of all the switching states is represented in Figure 2.

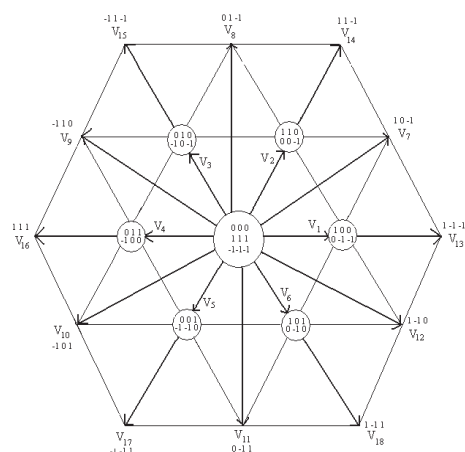


Figure 2. Space vector diagram

The space vector diagram consists of two hexagons, the inner hexagon and the outer hexagon. A three level inverter has basically 27 switching states out of which three are zero states and the remaining twenty four states are the active states. The zero states produce a zero vector where as the twenty four active states produce eighteen different voltage vectors. These eighteen active vectors are classified as small, medium and large voltage vectors based on their magnitude. This classification is shown in Table 1.

TABLE 1
CLASSIFICATION OF VOLTAGE VECTORS

Type	Vector numbers	Magnitude
Small	$V_1, V_2, V_3, V_4, V_5, V_6$	$0.5 V_d$
Medium	$V_7, V_8, V_9, V_{10}, V_{11}, V_{12}$	$0.866 V_d$
Large	$V_{13}, V_{14}, V_{15}, V_{16}, V_{17}, V_{18}$	V_d

These voltage vectors are selected accordingly so as to provide the voltages to the induction motor.

3. Principle of DTC

The electromagnetic torque of 3-phase induction motor is given by [1],

$$T_e = \frac{3 P}{2} \frac{L_m}{\sigma L_s L_r} |\psi_r| |\psi_s| \sin \eta \quad (1)$$

Where ψ_r and ψ_s are the rotor and stator flux linkages and η is the angle between the fluxes as shown in Figure 3 and σ is the leakage coefficient.

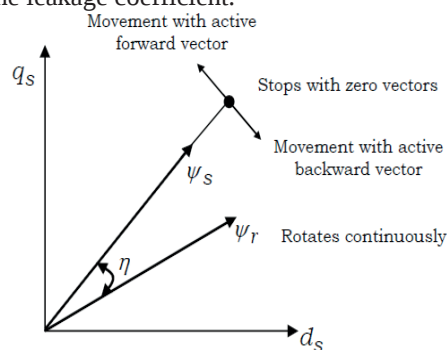


Figure 3. ψ_s movement along with ψ_r

The direct torque control of induction motor fed by a



three level NPC inverter is as shown in Figure 4.

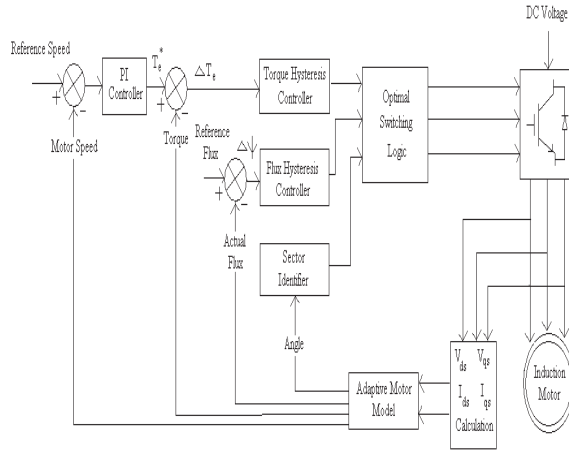


Figure 4. Block diagram of the DTC of Induction motor with PI controller

According to this block diagram, the scheme includes two hysteresis controllers. They are the torque hysteresis and the flux hysteresis controllers. The flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory. The torque controller determines the time duration of the zero vector, which keeps the developed electromagnetic torque within the defined hysteresis band.

The adaptive motor control block provides the information related to the actual torque, speed, flux and the angle to the hysteresis torque and flux controllers and the sector estimator blocks. The stator flux, torque and the stator flux linkages phase angle can be estimated by using the equations (2) - (4).

$$\Psi_s = \int (V_s - R_s i_s) dt \quad (2)$$

$$T_e = \frac{3}{2} \frac{P}{2} (i_{qs} \Psi_{ds} - i_{ds} \Psi_{qs}) \quad (3)$$

$$\theta = \tan^{-1} \left(\frac{\Psi_{qs}}{\Psi_{ds}} \right) \quad (4)$$

The PI controller employed in the system results in the torque command signal. The optimal switching logic block generates the control signals S_a , S_b , S_c to the three level inverter.

If the stator flux increase is required then S_ψ is set as 1 and if the stator flux decrease is required then S_ψ is set as zero. If the torque increase is required then S_T is set as 1, if the torque decrease is required then S_T is set as -1 and if the torque is not changed then $S_T=0$.

For the anticlockwise rotation or forward rotation the conditions are defined as in (5).

$$\begin{aligned} \text{If } T_e^* - T_e &\geq \Delta T_e & \text{then } S_T &= 1 \\ \text{If } T_e &\geq T_e^* & \text{then } S_T &= 0 \end{aligned} \quad (5)$$

For the clockwise rotation or reverse rotation the conditions are as shown in (6).

$$\begin{aligned} \text{If } T_e^* - T_e &\leq -\Delta T_e & \text{then } S_T &= -1 \\ \text{If } T_e &\leq T_e^* & \text{then } S_T &= 0 \end{aligned} \quad (6)$$

4. Modulation Strategy of three level DTC

The space vector diagram of the three level inverter is partitioned into twelve sectors by using a diagonal between the adjacent short vector and the medium vector [10], [11]. This partitioned space vector diagram is as shown in Figure 5. The adaptive motor model shown in Fig. 4 generates the sector angle as one of the output signals. Based on this angle, the sector number will be selected. For example, if the angle is in the range of $23\pi/12$ to $\pi/12$, that corresponds to sector 1. According to the DTC control principle, the voltage vectors should be selected based on the increase or decrease of the torque and flux. In order to select the voltage vectors, the sector selection should be done primarily. This sector selection is done based on the Table 2.

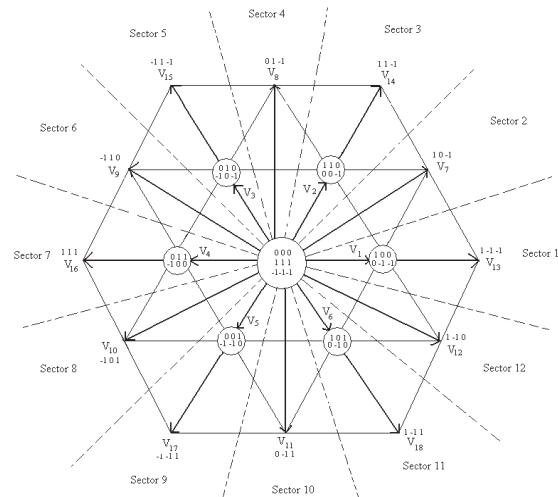


Figure 5. Space vector diagram for three level DTC

TABLE 2
SELECTION OF THE SECTORS

Flux	Torque	Selected Sector Number
Increase	Increase	$S_m = S_{n+1}, S_{n+2}$
Increase	Decrease	$S_m = S_{n-1}, S_{n-2}$
Decrease	Increase	$S_m = S_{n+4}, S_{n+5}$
Decrease	Decrease	$S_m = S_{n-4}, S_{n-5}$
No Change		Zero Vector

In the table, S_m represents the selected vector and S_n represents the sector where the current flux linkage is located. Variable n is selected between 1 and 12. If the value of m is over 12, m is forced to be $m-12$. If m is less than 1, then m is forced to be $m+12$.

The vector selection rules are framed and can be summarized as shown below.

(a) Select the vectors based on the demands of the flux and torque as shown in Table 2.

(b) Large vectors and the medium vectors should be selected to increase the DC bus utilization.

(c) Middle vectors can switch to the small and large



vectors freely.

(d) Small vectors can switch to the zero vectors easily.

(e) When small vectors are available select the vector which can meet the neutral point balance.

The above vector selection methods ensure the safe operation of the three level inverter.

Take location of stator flux linkage in sector S1 for instance, when torque modulation signal ST and flux linkage modulation signal SF are equal to 1, the voltage vectors V2, V7 and V14 located in sectors 2 and 3 can be chosen according to the Table 1. Actually, there are altogether four selective switching states because V2 corresponds to two switching states. In order to assure no excessive voltage amplitude jumping, vectors should be avoided changing from 1 to -1 and -1 to 1 directly. Considering that the use of medium vectors and small vector lead to the neutral point voltage floating and move towards different directions, therefore, the selecting of medium vectors are inevitable, and the key point of solving the neutral voltage floating problem is how to select and use small vectors reasonably.

It has been observed that composing small vectors located in different place will result in the neutral point voltage moving towards different directions. Take the medium vector 10-1 for instance, when we use the following seven segment composing take turns -1-1-1, 0-1-1, 10-1, 110, 110, 10-1, 0-1-1, -1-1-1 which is named N groups vector composition, then the neutral point voltage moves up fixedly. While using 111, 100, 10-1, 0-1-1, 0-1-1, 10-1, 110, 111 which is named P groups vector composition, the neutral point voltage moves down fixedly. Based on the different characteristics of neutral point voltage floating in N and P group vector composition, the presented modified modulation strategy of three-level inverter take the measure of hysteresis control on the neutral point voltage to suppress the neutral point voltage floating [12].

5. Sliding mode speed control for DTC

The cage induction motors are very economical, rugged, reliable and available in the ranges of fractional horse power to multi megawatt capacity. However, the induction motor drives exhibit significant nonlinearities in high performance control methods due to parameter variation and load torque disturbances. To overcome these problems, variable structure control (VSC) with sliding mode control (SMC) is proposed. A SMC with a VSC is basically an adaptive control that gives robust performance of a drive with parameter variation and load torque disturbances. This control is nonlinear and can be applied to a linear or nonlinear plant. In the SMC, the drive response is forced to track or along a predefined trajectory or reference model in a phase plane by a switching control algorithm, irrespective of the plant's parameter variation and load disturbance. In this paper, SMC based speed controller is proposed and tested for various load torque disturbances.

The SMC in performance is somewhat similar to a Model Reference Adaptive Control (MRAC), but the design and implementation of SMC is simpler. The phase plane diagram of SMC was given in [13]. SMC can be applied to induction motors for applications such as robot drives, machine tool control, etc. In this paper, a novel variable

structure control law with an integral sliding mode surface for speed control is proposed to compensate the uncertainties that are present in the system. The block diagram of SMC based CDTC drive is as shown in Figure 6 [14].

The electromechanical equation of an induction motor is described as shown in (7).

$$T_e = J \frac{d\omega_m}{dt} + B\omega_m + T_L \quad (7)$$

Where J and B are the inertia constant and the viscous friction coefficient of the induction motor system respectively, T_L is load torque, T_e is the electromagnetic torque of induction motor and ω_m is the rotor mechanical speed. The electromechanical equation can be modified further as shown in (8).

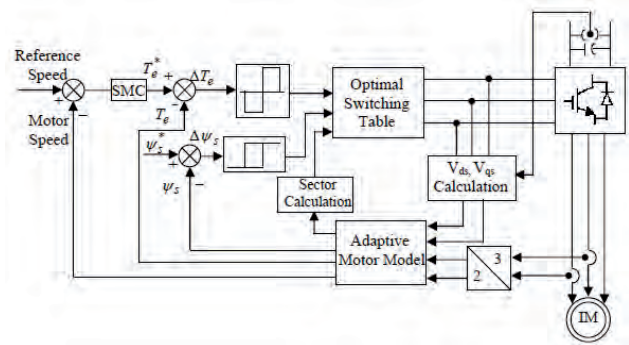


Figure 6. Block diagram of the proposed SMC based DTC drive

$$\dot{\omega}_m + a\omega_m + d = bT_e \quad (8)$$

Where $a = B/J$, $b = 1/J$, $d = T_L/J$.

Consider the electromechanical equation (9) with uncertainties as shown below.

$$\dot{\omega}_m = -(a + \Delta a)\omega_m - (d + \Delta d) + (b + \Delta b)T_e \quad (9)$$

Δa , Δb and Δd represents the uncertainties of the terms a , b and d respectively introduced by system parameters J and B . Consider the tracking speed error as given in (13).

$$e(t) = \omega_m^*(t) - \omega_m(t) \quad (10)$$

The sliding variable with integral component can be defined as (11)

$$S(t) = e(t) - \int_0^t (h - a)e(\tau) d\tau \quad (11)$$

Where h is a constant gain. The h must be chosen so that the term $(h-a)$ is strictly negative and hence $h < 0$. Based on the switching surface, a switching control that guarantees the existence of sliding surface, a speed controller is defined as [15]-[18],

$$f(t) = he(t) - \beta \text{sgn}(S(t)) \quad (12)$$

where β is the switching gain and $\text{sgn}(\cdot)$ is the sign function defined as

$$\begin{aligned} \text{sgn}(S(t)) &= +1 \text{ --- if } S(t) > 0 \\ \text{sgn}(S(t)) &= -1 \text{ --- if } S(t) < 0 \end{aligned} \quad (13)$$

The gain β must be chosen so that $\beta \geq x(t)$ for all the times Where $x(t)$ is the lumped uncertainty defined as



$$\dot{x}(t) = -\Delta a \omega_m(t) - \Delta d(t) + \Delta b T_e(t) \quad (14)$$

Consider the Lyapunov function given in (14)

$$V(t) = 1/2(S(t))^2 \quad (15)$$

Using the Lyapunov's direct method, it is found that $V(t)$ is clearly positive definite, derivative of $V(t)$ is negative definite and $V(t)$ tends to infinity as $S(t)$ tends to infinity, and then the equilibrium at the origin $S(t) = 0$ is globally asymptotically stable. Therefore $S(t)$ tends to zero as the time t tends to infinity. All trajectories starting off the sliding surface $S=0$ must reach it in finite time and then will remain on this surface. This system's behavior on the sliding surface is usually called sliding mode. When the sliding mode occurs on the sliding surface, then, $S(t) = dS(t) = 0$ and the tracking error $e(t)$ converges to zero exponentially. Finally, the reference torque command

T_e^* can be obtained as given below.

$$T_e(t) = \frac{1}{b} \left[(h\dot{e}) - \beta \operatorname{sgn}(S) + a^* \omega_m + \dot{\omega}_m + d^* \right] \quad (16)$$

This proposed sliding mode speed control resolves the speed tracking problem for DTC of induction motor drive.

6. Results and Discussion

The dynamic performance of direct torque controlled induction motor using modified modulate strategy of three-level inverter is observed by developing a Simulink model of the whole system. Parameters of the induction motor used in this paper are as shown below.

Stator resistance = 1.57 Ohms,

Rotor resistance = 1.21 Ohms

Magnetizing inductance = 0.165H,

Stator leakage inductance = 0.17H

Rotor leakage inductance = 0.17H,

Number of pole pairs = 4,

$J = 0.089 \text{ Kg-m}^2$.

For the simulation, the reference flux is taken as 1wb.

Reference speed is set to 1200 rpm. Figure 7 shows the simulink model of the three level DTC of induction motor that employed a PI controller. Figure 8 shows the simulink model of the three level DTC of induction motor that employed a sliding mode controller.

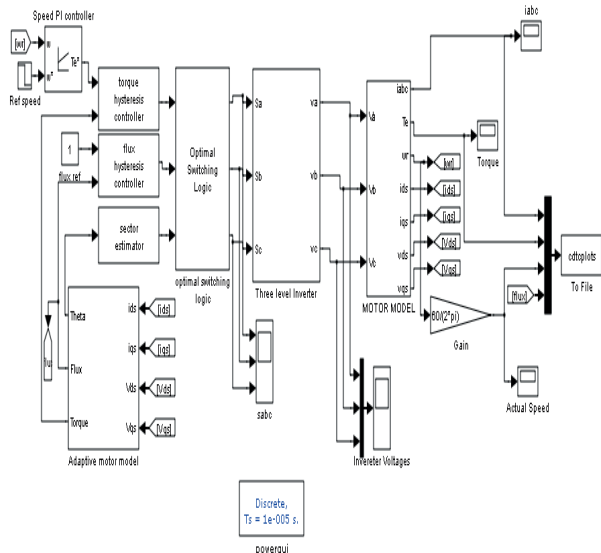


Figure 7. Simulink model of the 3 level DTC with PI Controller

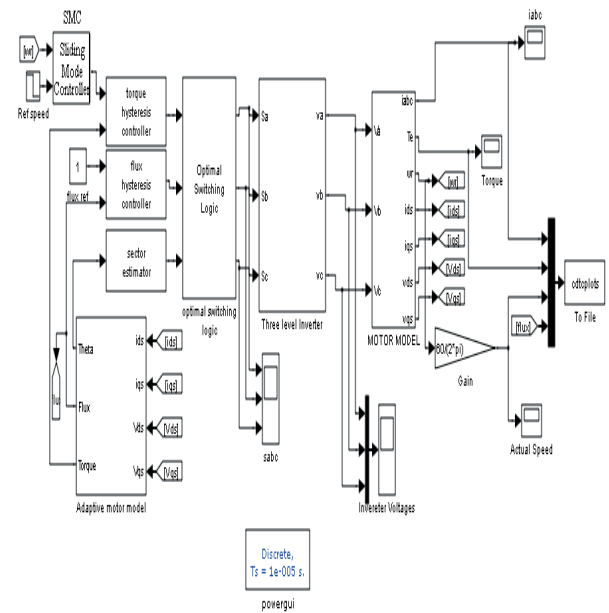


Figure 8. Simulink model of the 3 level DTC with SMC

For the simulation, the reference flux is taken as 1wb. The values, which have chosen for integral switching surface variable structure speed controller, are $h = -1000$ and $\beta = 5$.

Different conditions such as transient, steady state, step change in load are tested and compared in the systems with and without Sliding mode controller. Performance of the drive with and without SMC for external load torque disturbance is observed and the results are shown below.

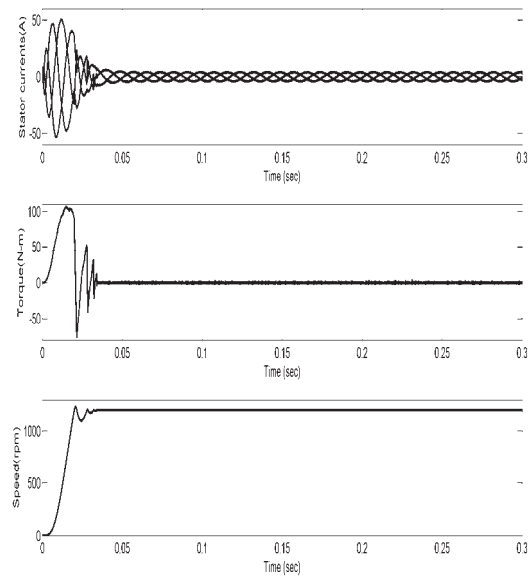


Figure 9. Starting transients

Figures 9, 10 and 11 shows the transient and steady state plots and transients during speed reversal from 1200 rpm to -1200 rpm at 0.5 seconds of the system with the proposed DTC system. The locus of the stator flux is shown in Figure 12.



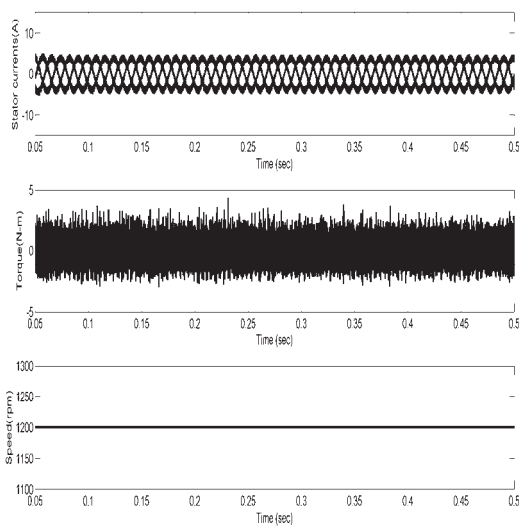


Figure 10. Steady state plots

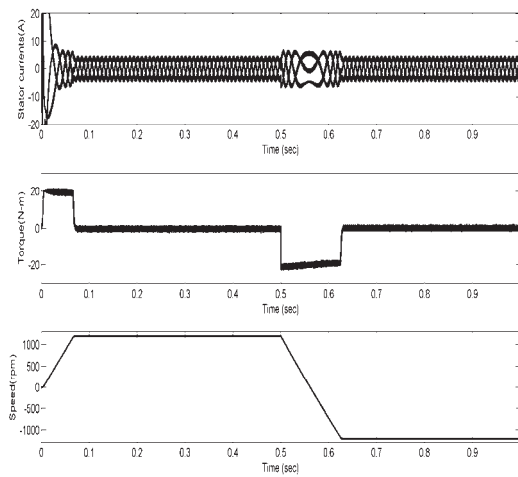


Figure 11. Transients during speed reversal from 1200 rpm to -1200 rpm at 0.5 sec

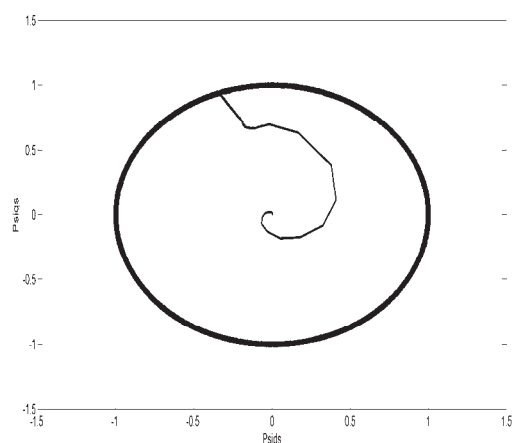


Figure 12. Locus of stator flux

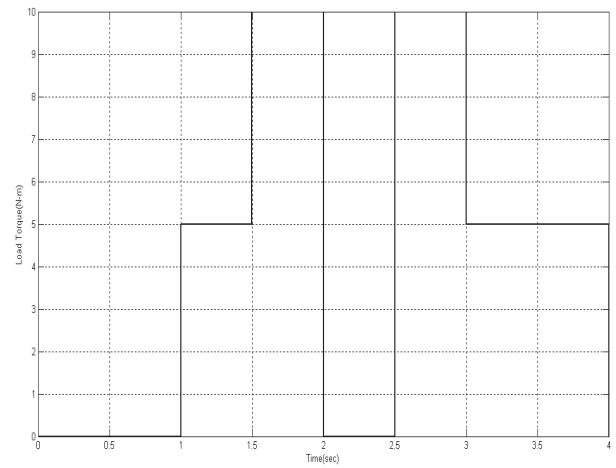


Figure 13. External load torque disturbance

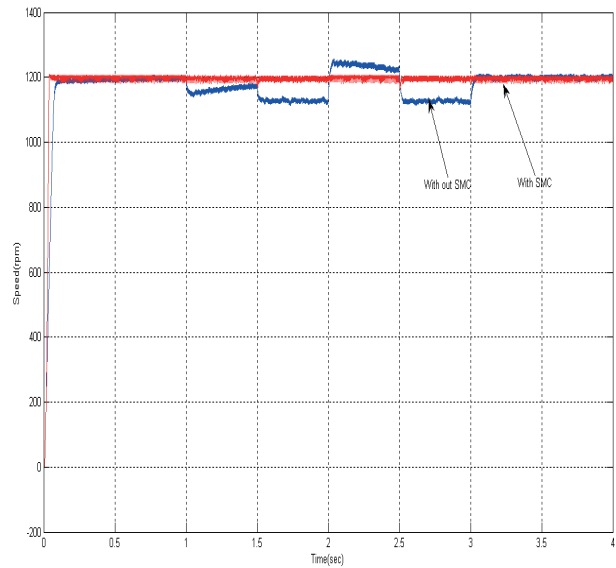


Figure 14. Speed comparison with and with out SMC

The proposed SMC is tested by considering different load torque disturbances. Figures 13 and 15 shows the external load torque disturbances. The speed response of the system with and without SMC is obtained as shown in Figures 14 and 16.

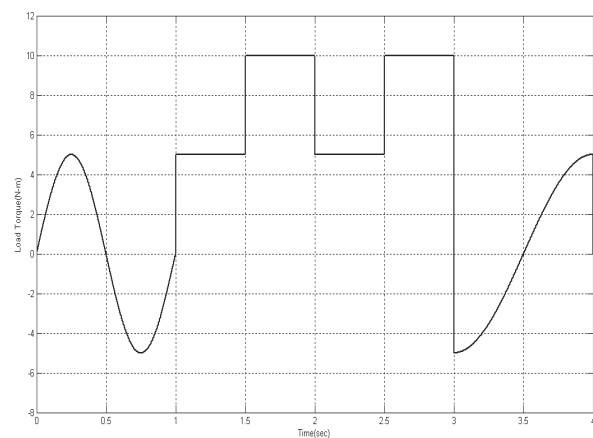


Figure 15. External load torque disturbance



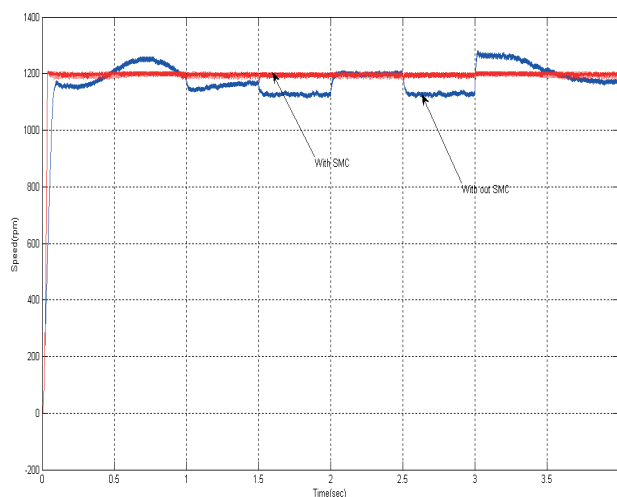


Figure 16. Speed comparison with and without SMC

7. Conclusion

To overcome the drawbacks such as high voltage jump, neutral point voltage drift in the conventional three level neutral point clamped inverter, a modified modulation strategy is proposed to implement DTC for an IM. The speed performance of the system is improved by employing an integral sliding mode controller.

The comparison of speed responses with and without sliding mode speed controller is validated by considering external load disturbance that consists of step changes in load torque. It can be observed that, when the load disturbance is added or removed the speed response is almost same as that of the reference speed in case of the proposed sliding mode speed controller. Thus, the speed tracking is not affected by the load torque. Finally it can be concluded that the SMC based DTC scheme gives a stable speed response even during the external load torque disturbance and hence provides the robustness for the system

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